AF INSTITUTE OF TECHNOLOGY

MODELING OF CAMOUFLAGE NETTING FOR RADAR CROSS SECTION ANALYSIS

THESIS

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AFIT/GE/ENG/89J-2

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Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
In Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Electrical Engineering

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June, 1989

Preface

The purpose of this study was to develop an analytical model of radar scattering for the US Army's currently deployed camouflage netting system. This model was needed to assist in the evaluation of developmental camouflage netting through prediction of radar cross section reduction. With this model, parameters measurable in the laboratory can be used to predict this performance.

The original intent was to determine a rule of thumb for predicting the performance of a netting system by correlating laboratory measurements made on flat stock camouflage cloth with data from recent flyover tests, but the amount of flyover data available for correlation was insufficient for a meaningful analysis. The research then turned toward developing a theoretical model on which to focus future efforts.

In writing this thesis, I received a great deal of help from others. In particular, my thesis advisor, Dr. Vital Pyati, provided continuing assistance throughout the research process. The other members of my committee, Lieutenant Colonel William Baker and Major Harry Barksdale, provided a valuable assistance in mathematical developments and field description, respectively. Mr. Thomas Conway, who served as my initial point of contact, Dr. Grayson Walker and Mr. Henry Atkinson of the Countersurveillance and Deception Division, Belvoir Research, Development, and Evaluation Center, which sponsored the effort, provided much additional assistance.

I must also thank my wife, Joan, and our children, Peg, Bill, and Christy, who provided the bulk my moral support.

John Bruce MacLeod

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Abstract

An analytical model for radar cross section reduction by the US Army's currently deployed camouflage netting system was developed. This model was needed to assist in the evaluation of developmental camouflage materials through prediction of radar cross section reduction. With this model, parameters measurable in the laboratory can be used to predict the performance of fabricated netting.

Using a physical optics approach to modeling, the net is modeled as a layer of lossy dielectric material. The layer is assumed to be a continuous, locally flat, and locally homogeneous medium. Relevant equations are then developed to predict radar cross section reduction. The constitutive parameters of interest are the complex permittivity and permeability and the effective thickness of the net. Methods of obtaining or approximating these values are discussed.

The development provides a prediction equation using a dyadic description of the electric fields on either side of the nets, developed from the constitutive parameters, from which a prediction of radar cross section reduction follows. Values for constitutive parameters are assumed to generate data for comparative purposes.

Using this model with the measured complex constitutive parameters of the net, an anticipated reduction of RCS can be predicted.

MODELING OF CAMOUFLAGE NETTING FOR RADAR CROSS SECTION ANALYSIS

I. Introduction

Background

On the modern battlefield, if a target can be seen, it can be hit; and if it can be hit, it can be killed. Vehicles can be seen because they possess multispectral signatures by which they can be identified. Survivability is enhanced by signature reduction, which can consist of using modes of operation which make detection difficult, visual camouflage, reduction of infrared emissions, noise attenuation and radar signature reduction (10:1-1–1-5). Radar signature reduction is necessary because detection radars seek out targets for all types of weapons systems, and increasing numbers of "smart" munitions rely on radars for terminal guidance. For this reason, reduction of radar signature, in the form of radar cross section (RCS), is an important area of research (14:187).

Ground vehicles are embedded in heavy clutter, presenting problems to the detection radar that are not found in seeking out aircraft. RCS of vehicles can be reduced through shaping or surface treatments or through a camouflage system which combines the two. Such camouflage systems may be a combination of paints, coatings, panels, blankets or netting (6).

To measure the effectiveness of a radar cross section reduction effort, a vehicle is treated with the developmental camouflage system, and subjected to an aircraft flyover. Although using aircraft with actual radars in a real environment provides the most meaningful data, this method is time consuming and prohibitively expensive. A cheaper method of determining radar cross section reduction is necessary.

Testing developmental materials in indoor ranges may be useful, as it provides inexpensive comparative data for the materials at various radar frequencies and allows security from observation (6). The data obtained from such tests, however, must reflect or correlate to actual performance in the field.

Problem Statement

The goal of this research is to develop a model of radar attenuation by camouflage netting materials. An important application of this work is that of correlation between measurements made in indoor radar range facilities to actual measurements from full scale flyovers.

Assumptions

The independent variables analyzed will be assumed to arise solely from the camouflage materials under test. Atmospheric effects, radar system losses, and other radar system dependent losses are ignored in this study.

Scope

This study will be confined to nets of the currently deployed lightweight radar scattering screening system described in Appendix A. Netting systems with similar radar scattering schemes would, however, be suitable for analysis under the proposed model. Frequencies of interest will be limited to 6–35 Ghz. This is the range of frequencies used for testing the radar properties of the netting system in accordance with the system's military specification, MILSPEC MIL-C-53004A(ME)(12:21).

Approach

The currently deployed lightweight radar scattering screening system will be modeled as a layer of lossy dielectric. High frequency techniques of physical optics will be used to develop a model with measurable descriptive parameters.

Sequence of Presentation

Chapter II is a literature rev'ˍw of radar attenuation modeling techniques. Basic concepts of radar cross section and modeling of nonlinear materials such as camouflage treatments are included.

Chapter III develops the relevant theory and the scattering model.

Chapter IV describes the application of the model in prediction of radar cross section reduction. Data reduction techniques and the methodology of the correlation process are discussed.

Chapter V finishes this study with conclusions and recommendations for applying the modeling techniques in radar cross section prediction.

II. Literature Review

Introduction

In order to model camouflage materials for radar cross section measurement, a basic understanding of radar and scattering is necessary. This literature review surveys the literature on both topics as they relate to radar attenuation measurement. The review consists of a description of radar cross section, and a discussion of the models of electromagnetic scattering.

Radar Cross Section

The detectability of a radar target is determined by the radar range equation:

$$\textit{Received signal energy} \approx \frac{P_{avg} G \sigma A_e t_{int}}{(4\pi)^2 R^4} \tag{1}$$

$$\begin{aligned} \text{where } P_{avg} &= \text{average transmitted power} \\ G &= \text{antenna gain} \\ \sigma &= \text{radar cross section of target} \\ A_e &= \text{effective antenna area} \\ t_{int} &= \text{integration time} \\ R &= \text{range} \end{aligned}$$

(22 : 185)

This equation has several forms, varying according to author preference and parameters of interest (23:64), (16:701),(2:67),(21:15).

From a survivability standpoint, the key variable of this equation is the radar cross section, because it is the only variable completely outside the control of enemy radar designers (21:15). Stimson describes radar cross section (RCS) as a combination of geometric cross section, reflectivity, and directivity and gave this simplified definition:

$$(\textit{power incident on target}) \times (\textit{radar cross section}) = \textit{power transmitted back} \tag{2}$$

(22:171). In the dependence of RCS on the power incident on the target, the attenuation and reflectivity provided by a camouflage netting system are of primary importance. Attenuation reduces the amount of power incident on the target, while reflection by the netting has a radar signature in its own right.

Radar cross section is important as a figure of merit for signature reduction. Skolnik noted that the utility of RCS lies in that it is both a measurable and derivable figure of merit (21:39–40). However useful RCS may be, the derivation of RCS by mathematical methods is complex for other than simple shapes. This derivation is done by breaking the object into smaller ones, and summing the contribution of each component. Crispin demonstrated that the importance of a given component depends on the frequency of the incident wave (9:973). Blacksmith cautioned, however, that formulæ can be accepted only after comparison to actual measurements (3:902).

Cross Section Measurement

Although measurement of the actual vehicle is the most realistic method of determining RCS, a method conducive to precise control is needed. Corriher stated good RCS measurements must be able to: correlate aspect angle and range, have enough data points to show scintillation, examine all frequencies and polarizations, have a signal to noise ratio high enough to examine the lowest RCS levels, possess a dynamic range great enough to preserve amplitude variation, give a real time monitoring capability, and record data (7:345). Knott amplified the requirements for radar cross section measurements and stated: "no prediction technique is all-encompassing and all codes have limitations. Therefore, it is necessary to test the final integrated weapons system, although portions of the system already may have been treated or investigated individually" (14:317).

Such measurements are made on a controlled radar measurement facility, or range. Such a range must have, as a minimum: a radar, recording instruments,

a target support and rotator, a low background environment and the test target (14:318). Methods for measuring high range resolution radar cross section may use nanosecond pulse radar, FM continuous wave radar, or frequency stepping radar (1:962).

Measurement errors arise from deviations from a plane wave striking the target, quadratic phase errors, and facility errors, which consist of high background noise levels and calibration errors (13:512–513). A rule of thumb for ranges using current technologies is measurements are accurate to .5 dB for static measurements and 2 dB for dynamic measurements. The error for relative measurements is somewhat better: approximately .1 dB error per 10 dB, depending on the linearity of the range's instrumentation (13:511). The difference in dynamic and static errors arise from the difficulty in controlling aspect angle and the inherent difficultly of dynamic versus static measurement (18:957).

Modeling Reflectivity and Attenuation

Power incident on an object is reflected, absorbed, or transmitted as shown in Figure 1, or in terms of tangential electric fields:

$$\mathbf{E}^i = \mathbf{E}^t + \mathbf{E}^r \tag{3}$$

where $\mathbf{E}^i$, $\mathbf{E}^t$, and $\mathbf{E}^r$ are the incident, transmitted and reflected fields, respectively. Assuming absorption is minimal, the reflection and transmission (or scattering and attenuation) properties of the net are of primary importance.

The complication of modeling camouflage netting arises from the material's properties in attenuating and scattering incident radar waves. The description of the reflected and transmitted fields from a layer of lossless dielectric are straightforward and can be found in basic electromagnetics texts (16:511–524), (5:142–170). In the case of a net specifically designed to scatter radar waves, the net must be considered a lossy dielectric, which complicates the solution, in that the permittivity

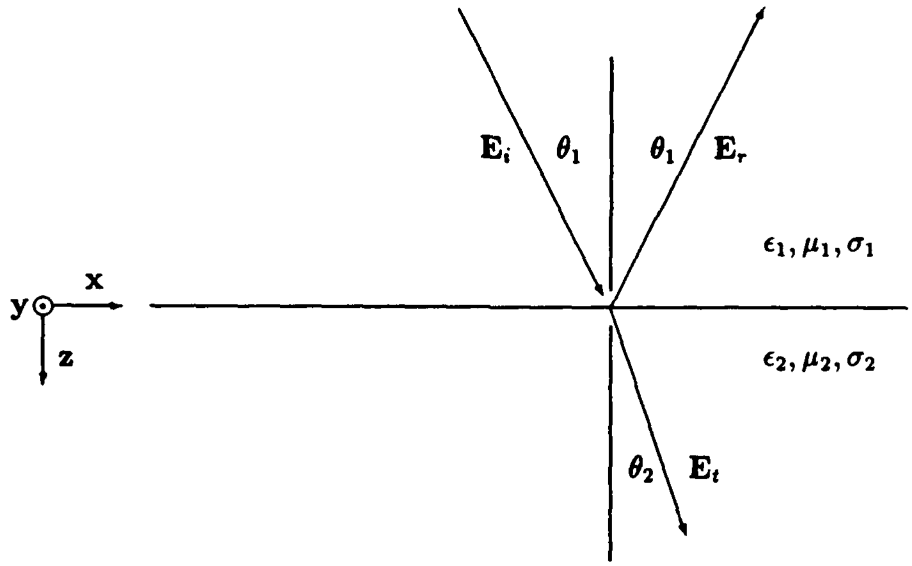

Figure 1. Plane Wave at Interface between Media

and permeability must be treated as complex quantities. Complex values of these two key variables leads to a necessity of a dyadic description of the reflectivity and transmission coefficients (20:473)

The reflected and transmitted fields, in terms of reflection and transmission coefficients are described by:

$$\mathbf{E}^r = \underline{\underline{R}}\,\mathbf{E}^i \quad \text{and} \quad \mathbf{E}^t = \underline{\underline{T}}\,\mathbf{E}^i \tag{4}$$

Where $\underline{\underline{R}}$ and $\underline{\underline{T}}$ are three-dimensional symmetric dyads. For planar media with properly chosen coordinate systems, these can be reduced to two-dimensional symmetric dyads. This means a complete description of the reflected and transmitted fields can be obtained with the coefficients $R_{||}$, $R_{\perp}$, $T_{||}$, and $T_{\perp}$, where the subscripts refer to the parallel or perpendicularly polarized components of the coefficients. These assume permeability μ and permittivity ϵ to be complex, describing a lossy medium (20:473).

At the plane interface,

$$R_{\parallel,\perp} = -(z_1 - z_2)/(z_1 + z_2) \tag{5}$$

$$T_{\parallel,\perp} = 2z_2/(z_1 + z_2) \tag{6}$$

where z_i is the complex impedance of the ith medium:

$$z_i^{\perp} = \frac{1}{\cos\theta_i}\sqrt{\frac{\mu_i}{\epsilon_i}} = \frac{\eta_i}{\cos\theta_i} \tag{7}$$

$$z_i^{\parallel} = \cos\theta_i\sqrt{\frac{\mu_i}{\epsilon_i}} = \eta_i\cos\theta_i \tag{8}$$

in which $\cos\theta_i = \left[1 - \left(\frac{k_1}{k_i}\right)^2 \sin^2\theta_1\right]^{1/2}$ and

$$k = \text{complex wave number of medium} = \omega\sqrt{\mu_1\epsilon_1}$$

$$\eta = \text{index of refraction of medium}$$

(20:473–474). Chen develops similar relationships in a coordinate free approach (5:171–175).

Kong noted that in remote sensing applications, it is necessary to model volume scattering effects by using layered media with a randomly fluctuating permittivity, ϵ, such that $\epsilon = \epsilon_1 + \epsilon_{1f}(r)$, where ϵ_1 is the mean permittivity and $\epsilon_{1f}(r)$ is the fluctuating component of the permittivity (15:517–518).

Conclusion

Several major obstacles present themselves in applying this model. The complexity of the relationships does not lend itself to rule of thumb computations. More importantly, the complex quantities of permittivity and permeablity must be determined. If these obstacles can be overcome, modeling can permit quicker radar cross section measurements at a lower cost, however, Crispin reminds the modeler that a vehicle's performance in an actual environment is what is being sought — not a geometrical approximation or scale model's performance (9:973).

III. *Theory*

Introduction

A camouflage netting system affects the radar signature of a target through attenuating and scattering of the incident radiation. The first mechanism serves to reduce the radar return from the target, while the second may increase it. A target under a camouflage net can be represented as shown in Figure 2. The target is

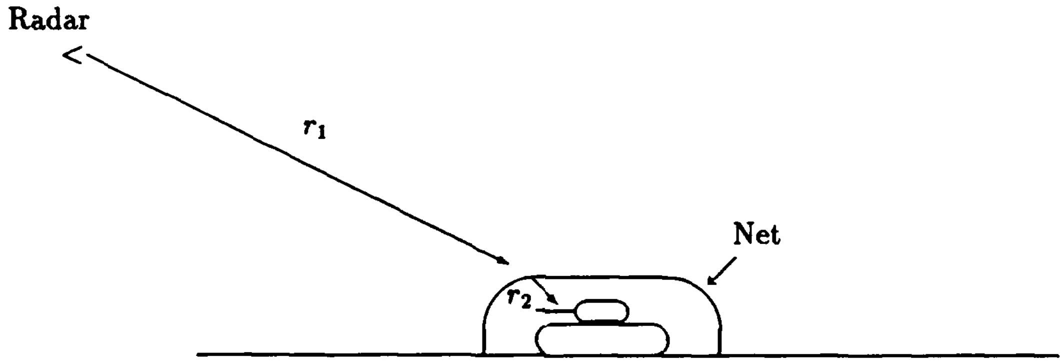

Figure 2. Target under Camouflage Net

completely covered by the net, which is a smooth surface intersecting the ground at all points of the perimeter. It is illuminated by a radar at a distance r_1. The net is separated from the target by a distance r_2, which is a minimum of 2 ft. A physical description of the netting system is included at Appendix A.

Modeling the Net

For modeling purposes, several simplifying assumptions will be made. The screen is modeled as an infinite flat layer with permittivity ϵ_2 and permeability μ_2, which are assumed to be complex, and thickness d. These assumptions are shown in Figure 3.

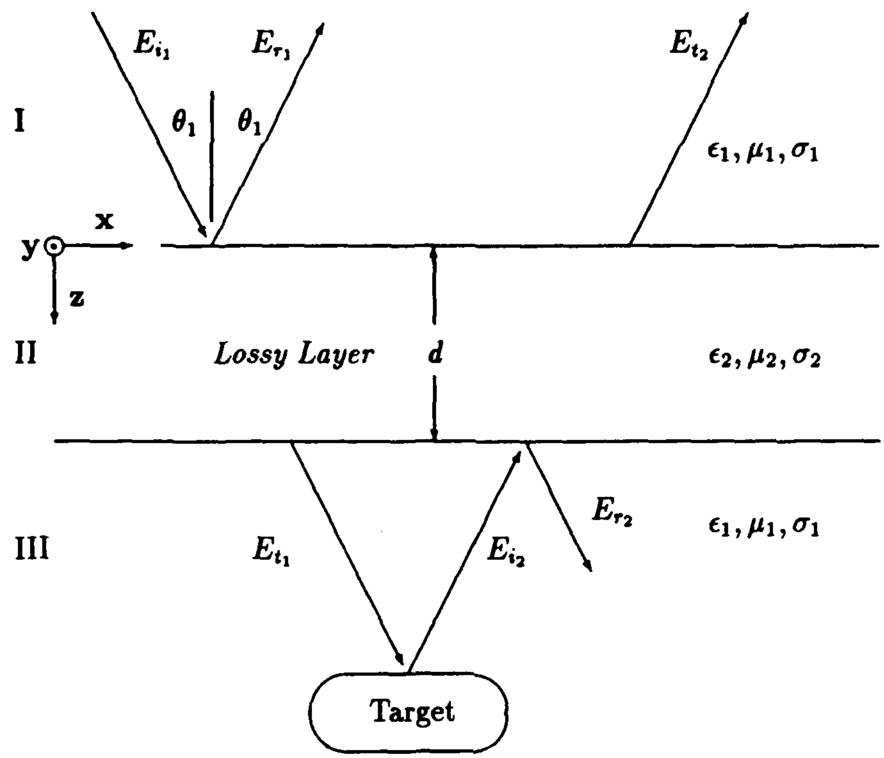

Figure 3. Target under Lossy Layer

If the net is assumed to be a zone of a sphere of radius R, the wavelength is much less than R ($\lambda \ll R$), making the net locally flat to an incident beam. For a typical deployment of a netting system, the diameter of the net is on the order of 20 meters (see Appendix A). For frequencies of 6–35 GHz, the dimensions of the net are much greater than the incident wavelengths (.05–.0086 meters). When these assumptions are coupled with the assumption that only backscattered energy is of interest, the treatment of the net as an infinite layer is reasonable.

The target is modeled as a circular flat plate. Although actual targets are complex shapes exhibiting multiple reflection patterns, the item of interest here is not the RCS of the target, but the reduction of the RCS caused by the presence of the net. To simplify the analysis, a simple target is selected. A circular flat plate,

symmetric about the z-axis, reduces the complexity of the problem by requiring the use of only two coordinates: z and either x or y to describe the geometry of the system.

The power received at the radar will consist of a part of the wave reflected from the net and a part transmitted through the net, reflected from the target, and transmitted back through the net. In terms of the electric fields,

$$E_{receiver} = \frac{(E_{r_1} + E_{t_2})}{4\pi r_1^2} \tag{9}$$

where r_1 is the range from the layer to the receiver, but

$$E_{t_2} = E_{i_2}\underline{\underline{T}}$$

where $\underline{\underline{T}}$ is the dyadic transmission coefficient of the layer, and

$$E_{i_2} = \underline{\underline{T}}E_{i_1}\sigma\frac{1}{(4\pi r_2^2)^2}$$

where σ is the radar cross section of the target. So

$$E_{receiver} = \left[\underline{\underline{R}} + \underline{\underline{T}}\,\underline{\underline{T}}\frac{\sigma}{(4\pi r_2^2)^2}\right]\frac{E_{i_1}}{(4\pi r_1^2)} \tag{10}$$

where r_2 is the distance from the layer to the target.

The reflection from the lower side of the layer, E_{r_2}, will also interact with the target, causing yet another wave incident on the bottom side of the layer. This wave will, in turn, be transmitted and reflected by the layer. This process will continue indefinitely. If multiple reflections are considered, this equation becomes

$$E_{receiver} = \left[\underline{\underline{R}} + \underline{\underline{T}}\,\underline{\underline{T}}\frac{\sigma}{(4\pi r_2^2)^2} + \underline{\underline{T}}\,\underline{\underline{R}}\,\underline{\underline{T}}\frac{\sigma^2}{(4\pi r_2^2)^4} + \underline{\underline{T}}\,\underline{\underline{R}}^2\underline{\underline{T}}\frac{\sigma^3}{(4\pi r_2^2)^6}\ \cdots\right]\frac{E_{i_1}}{(4\pi r_1^2)} \tag{11}$$

Regrouping, this becomes

$$E_{receiver} = \frac{E_{i_1}}{(4\pi r_1^2)}\left\{\underline{\underline{R}} + \frac{\sigma}{(4\pi r_2^2)^2}\underline{\underline{T}}\left[\underline{\underline{I}} + \underline{\underline{R}}\frac{\sigma}{(4\pi r_2^2)^2} + \underline{\underline{R}}^2\frac{\sigma^2}{(4\pi r_2^2)^4}\ \cdots\right]\underline{\underline{T}}\right\} \tag{12}$$

where $\underline{\underline{I}}$ is the identity dyad.

Simplifying this with a binomial series description yields

$$E_{receiver} = \frac{E_{i_1}}{(4\pi r_1^2)} \left\{ \underline{\underline{R}} + \frac{\sigma}{(4\pi r_2^2)^2} \underline{\underline{T}} \left[\underline{\underline{I}} - \underline{\underline{R}} \frac{\sigma}{(4\pi r_2^2)^2} \right]^{-1} \underline{\underline{T}} \right\} \tag{13}$$

The value of $E_{receiver}$ will have parallel and perpendicularly polarized components, regardless of the polarization of the transmitted field, due to the dyadic nature of the variables in Equation 13.

For the purpose of these equations, the definition of radar cross section is most conveniently stated as

$$\sigma = \frac{scattered\ power}{incident\ power\ density} = \frac{4\pi r^2 S_r}{S_{inc}} \tag{14}$$

where S_r =scattered power density at distance r, and S_{inc} =power density on target (16:702). These power values are obtained from electric fields by

$$S = \frac{E_\perp^2 + E_\parallel^2}{2Z} \tag{15}$$

where Z is the impedance of the medium ($Z_{air} = 376.7\ \Omega$) (16:499).

The behavior of the wave at the layer is shown in Figure 4. A wave in region I is incident on the layer at an arbitrary angle θ_1. Portions of the wave's energy pass through the layer (region II) and into region III, which has the same dielectric properties as region I.

The fields on either side of the layer are related by

$$\begin{bmatrix} E_1 \\ H_1 \end{bmatrix} = [A] \begin{bmatrix} E_3 \\ H_3 \end{bmatrix} \tag{16}$$

where

$$A = \begin{bmatrix} \cos\alpha_2 & iz_2 \sin\alpha_2 \\ (i/z_2)\sin\alpha_2 & \cos\alpha_2 \end{bmatrix} \tag{17}$$

$$z_m^\perp = \frac{1}{\cos\theta_m} \sqrt{\frac{\mu_m}{\epsilon_m}} \tag{18}$$

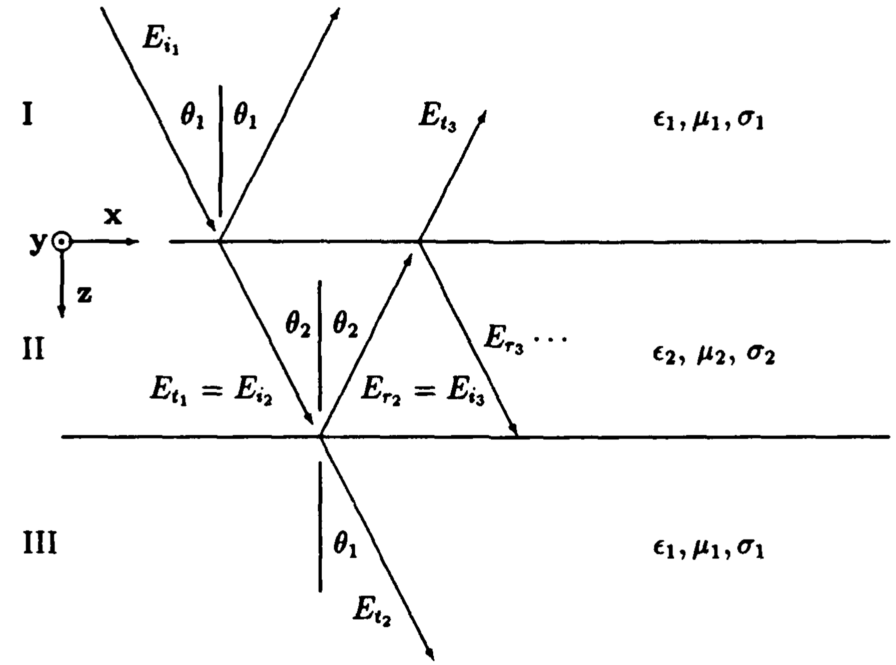

Figure 4. Plane Wave Incident on Infinite Lossy Layer

$$z_m^{\parallel} = \cos\theta_m \sqrt{\frac{\mu_m}{\epsilon_m}} \tag{19}$$

$$\alpha_2 = k_2 d\sqrt{1 - (k_1/k_2)^2 \sin^2\theta_1)} \tag{20}$$

and the effective input impedance is

$$Z = z_2 \frac{z_3 - iz_2 \tan\alpha_2}{z_2 - iz_3 \tan\alpha_2} \tag{21}$$

The angle a given ray takes inside the layer will depend on the index of refraction of the layer, or

$$\theta_2 = \sin^{-1}\left[\frac{\sqrt{\epsilon_2\mu_2}}{\sqrt{\epsilon_1\mu_1}} \sin\theta_1\right] \tag{22}$$

If medium 1 and medium 3 are the same, the reflection and transmission coefficients can then be described by

$$R = \frac{i(z_1^2 - z_2^2)\tan\alpha_2}{2z_1z_2 - i(z_1^2 + z_2^2)\tan\alpha_2} \tag{23}$$

$$T = \frac{2z_1z_2}{2z_1z_2\cos\alpha_2 - i(z_2^2 + z_1^2)\sin\alpha_2} \tag{24}$$

With these equations, the fields on both side of the layer can be described, given the characteristics of the incident wave, its incidence angle, θ_i, and the thickness of the layer, d (20:482–483). With the range from the layer to the receiver and the layer to the target, the field at the receiver can be described as well.

If the deployed camouflage netting system is modeled as a zone of a sphere, rather than as an infinite plane, the net can still be modeled as being locally flat. The angle of incidence, θ_i, will have to be adjusted to reflect the change in orientation of the tangent plane at the net's surface. The angle of incidence on the target will vary from 0, when the propagation vector is normal to the ground plane, to 90 degrees at grazing angles. The angle of incidence on the net will be the angle between the propagation vector and the normal to the tangent plane at the point of incidence on the net. These two angles ($\theta_{i_{tgt}}$ and $\theta_{i_{net}}$, respectively) will be equal only at $\theta_{i_{tgt}} = \theta_{i_{net}} = 0$, as shown in Figure 5.

By simple geometry,

$$R = \frac{b^2 + h^2}{2h}$$

and by the law of sines,

$$\frac{R}{\sin(\pi - \theta_{i_{tgt}})} = \frac{R}{\sin\theta_{i_{net}}}$$

but $\sin(180 - \theta_{i_{tgt}}) = \sin(\theta_{i_{tgt}})$, so

$$\theta_{i_{net}} = \sin^{-1}\left(\frac{R-h}{R}\sin\theta_{i_{tgt}}\right) \tag{25}$$

where $\theta_{i_{net}}$ is the θ_i used in previous equations.

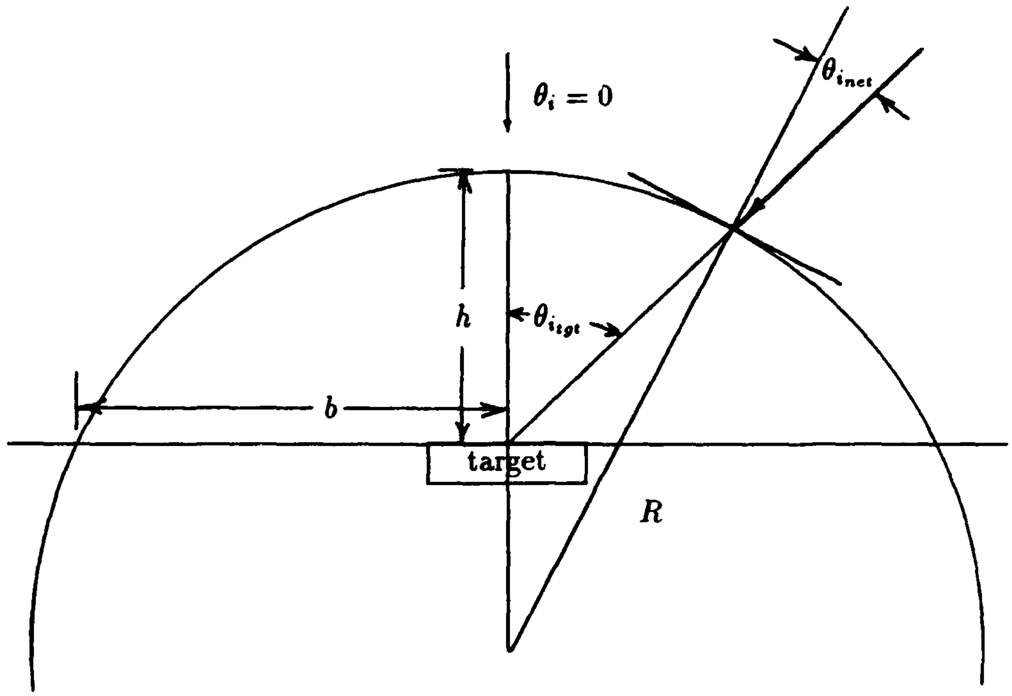

Figure 5. Camouflage Net Modeled as Zone of Sphere

If typical values ($h = 5$ m and $b = 10$ m) are substituted into this equation, R becomes 12.5 m, and it can be seen that the two angles are indeed equal at normal incidence. At grazing incidence ($\theta_{i_{tgt}} = 0$), $\theta_{i_{net}} = 36.87$ degrees, which will be the maximum value of $\theta_{i_{net}}$.

Modeling Electrical Properties of the Medium

The key to describing the fields on either side of the layer lies in modeling the electrical properties of the net material. Several possible methods present themselves:

- Model the scattering of individual scatterers
- Model the net as a random presence
- Model the net as an equivalent continuous medium

The first possibility is discarded as too complex. Random variables in this approach include the size, orientation, and presence of individual scatterers in the camouflage cloth as well as a random presence of the cloth in the net. For a given path through the net, the scattering material may be totally absent, consist of a single layer of scattering cloth, or consist of two or more layers of the cloth. Such presence of cloth, the presence the scatterers imbedded in the cloth, and the edge effects of the holes of various configurations in the net are all random variables in this approach.

Modeling the Layer as a Random Presence

Modeling the net as a random presence requires a physical optics approach. Physical optics is a high frequency technique for analysis of electromagnetic scattering which relies on analysis of the illuminated side of the target only. Each point on the illuminated side of the target is treated as a point on an infinite tangent plane. To use physical optics methods to examine the scattering and attenuation of camouflage netting, the net is modeled as a layer with holes in it. These holes are of random size, shape, and spacing. Their effect will be to diffract incident radiation.

Application of physical optics techniques requires several assumptions to solve the Chu-Stratton integrals, which describe the scattered fields:

$$\mathbf{E}^s(\mathbf{r}) = \frac{1}{4\pi}\int_S [(\hat{\mathbf{n}}' \times \mathbf{E}^T)\times\nabla'\psi_0 + i\omega\mu(\hat{\mathbf{n}}' \times \mathbf{H}^T)\psi_0 + (\hat{\mathbf{n}}' \cdot \mathbf{E}^T)\nabla'\psi_0]ds' \tag{26}$$

$$\mathbf{H}^s(\mathbf{r}) = \frac{1}{4\pi}\int_S [(\hat{\mathbf{n}}' \times \mathbf{H}^T)\times\nabla'\psi_0 + i\omega\epsilon(\hat{\mathbf{n}}' \times \mathbf{E}^T)\psi_0 + (\hat{\mathbf{n}}' \cdot \mathbf{H}^T)\nabla'\psi_0]ds' \tag{27}$$

where $\mathbf{E}^s(\mathbf{r})$ = scattered electric field

$\mathbf{H}^s(\mathbf{r})$ = scattered magnetic field

$\hat{\mathbf{n}}'$ = unit vector normal to surface at $\mathbf{r}'$

$\mathbf{E}^T$ = total electric field at $\mathbf{r}'$

$\mathbf{H}^T$ = total magnetic field at $\mathbf{r}'$

ψ_0 = free space Green's function

ds' = differential element of surface area S (20 : 35)

The integrals are assumed to be applied to a nonclosed surface, or to a finite portion of a closed surface, and the described fields arise from the illuminated surface only. At the shadow boundary, the fields drop to zero. This approximation is acceptable if λ is much smaller than the dimensions of the illuminated object.

The second assumption is the object must be far away from the antenna. The minimum distance is arbitrarily set at $r > 2D^2/\lambda$, where D is the largest dimension of the object.

Finally, the radius of curvature of the target must be much greater than the wavelength, λ, allowing the tangent plane approximation to be used.

In the case of a radar scattering camouflage net, all these assumptions are reasonable. When applied to the basic Chu-Stratton integrals, they lead to the equations used to develop the Fresnel coefficients, from which Equations 23 and 24, are derived (20:55,475).

The problem then becomes the description of the illuminated surface. The surface is treated as a perfect conductor with holes of random size and spacing. These holes cause Frauenhofer diffraction, since the size of the holes are on the order of the wavelength of interest (λ = .05 to .0086 meters). The incoming wave is assumed to be plane, because the distance from the radar to the net is much larger than the dimensions of the holes. On the underside of the layer, the distance from the net to the target relative to the dimensions of the holes is not as large, however,

the approximation is still reasonable.

For a round hole, the irradiance, I is

$$I(P) = \left[\frac{2J_1(kaw)}{kaw}\right]^2 I_o \tag{28}$$

where	I_o	=	$ED/\lambda^2 R^2$
	P	=	Point on target
	E	=	total energy incident on aperture
	D	=	area of aperture, πa^2
	λ	=	wavelength of incident radiation
	J_1	=	Bessel function of the first kind
	a	=	radius of aperture
	w	=	radial coordinate of P on target
	k	=	wave number of incident radiation, ω/c (4 : 396)

To describe the diffracted field in terms of energy, the irradiance can be integrated over target area and time to determine the energy, E, incident on the target:

$$E = \iint_A I \, dA \, dt \tag{29}$$

For a target with multiple openings of the same size and shape, the irradiance at a point becomes

$$I(p,q) \sim NI^{(0)}(p,q) \tag{30}$$

where p and q are coordinates of a point on the target, $I^{(0)}$ is the irradiance caused by a single opening, and N is the number of openings (4:396-400). For a camouflage netting system with randomly distributed and sized holes, this equation must be modified to account for the random variables.

The difficulty in this approach is in determining a description of random distribution of the holes in the layer and their variation in size.

Modeling the Layer as a Continuous Medium

Modeling the net as an equivalent continuous medium assumes an electromagnetic field quantity, ψ (e.g. $\vec{E}$ or $\vec{H}$) is a random variable which can be described as

$$\psi = <\psi> + \tilde{\psi} \tag{31}$$

where $<\psi>$ is the ensemble average, or mean component and $\tilde{\psi}$ is the fluctuation about the mean. Note that $<\tilde{\psi}> = 0$.

The equivalent continuous medium is described by an effective dyadic permittivity, $\underline{\underline{\epsilon}}$, or an effective dyadic susceptibility, $\underline{\underline{\chi}}$. Lang determined $\underline{\underline{\epsilon}}$ and $\underline{\underline{\chi}}$ to be

$$\underline{\underline{\epsilon}} = \underline{\underline{I}} + \frac{(2\pi)^3\rho}{k_0^2}\tilde{\underline{\underline{t}}}(\underline{k}, \underline{k}') \tag{32}$$

$$\underline{\underline{\chi}} = \underline{\underline{\epsilon}} - \underline{\underline{I}} \tag{33}$$

where $\underline{\underline{I}}$ = the unit dyadic

ρ = number density of scatterers

k_0^2 = $\omega^2\mu_o\epsilon_o$

$\tilde{\underline{\underline{t}}}(\underline{k}, \underline{k}')$ = dyadic transition kernel

$\underline{k}$ = wave vector of medium (17 : 4-3)

The difficulty in this approach lies in determining the dyadic transition kernel, $\tilde{\underline{\underline{t}}}(\underline{k}, \underline{k}')$, which is complicated for other than in the low frequency limit or Rayliegh region(17:4-3). A complex permittivity can, however, be measured in the laboratory using inverse techniques, and a dyadic description can be developed for $\underline{\underline{\epsilon}}$ by taking measurements at parallel and perpendicular polarizations. Determining $\underline{\underline{\epsilon}}$ is discussed in Chapter 4.

Descriptive Parameters

The anticipated reduction of a target's radar cross section can be determined from the equations developed in this chapter. For a given target of cross section σ,

the calculation will require the basic parameters of the medium and radar frequency, ω $(2\pi f)$, μ, and ϵ. From these basic parameters, the complex wave number k and the complex impedances z_m can be computed and combined with d and θ in equations 18 and 19, and with 20, to determine α. In turn, α is used with d in equations 23 and 24 to determine the Fresnel coefficients.

Equation 13 uses these coefficients with σ and r_2 to determine the energy received at the antenna, $E_{receiver}$. Given the energy transmitted, E_t, the incident field is calculated by the relation:

$$E_{i_1} = \frac{E_t}{4\pi r_1^2} \tag{34}$$

where E_t is the transmitted energy. Rewriting Equation 13 in terms of the transmitted energy yields

$$E_{receiver} = \frac{E_t}{(4\pi r_1^2)^2}\left\{\underline{\underline{R}} + \frac{\sigma}{(4\pi r_2^2)^2}\underline{\underline{T}}\left[\underline{\underline{I}} - \underline{\underline{R}}\frac{\sigma}{(4\pi r_2^2)^2}\right]^{-1}\underline{\underline{T}}\right\} \tag{35}$$

The quantities to be compared are the energy received at the antenna, $E_{receiver}$ for a target with and without a deployed camouflage net. The calculation required for an unconcealed vehicle is simply

$$E_{receiver} = \frac{\sigma E_t}{(4\pi r_1^2)^2} \tag{36}$$

The ratio of $E_{receiver}$ due to a target with a net to one without a net is obtained by combining these last two equations to yield

$$Attenuation\ Ratio = \frac{1}{\sigma}\left\{\underline{\underline{R}} + \frac{\sigma}{(4\pi r_2^2)^2}\underline{\underline{T}}\left[\underline{\underline{I}} - \underline{\underline{R}}\frac{\sigma}{(4\pi r_2^2)^2}\right]^{-1}\underline{\underline{T}}\right\} \tag{37}$$

This equation states that the field received at the radar due to reflections from a target of radar cross section σ, is attenuated by a factor depending on the radar cross section of the vehicle and the deployed net's parameters. These parameters depend on the manner in which the net is erected (r_2) and the manner in which the

net is fabricated ($\underline{\underline{R}}$ and $\underline{\underline{T}}$). The dyadic reflection coefficients are in turn dependent upon the complex constitutive parameters ϵ and μ and the radar-dependent variables of wavelength and angle of incidence.

Conclusion

The two approaches result in forms requiring the description of key variables in random form. Modeling the layer as a random presence requires the description of holes in terms of size, shape and spacing. In the case of describing the layer as a continuous medium, the model requires a description of a complex dyadic permittivity. Given a description of the effective constitutive parameters, the anticipated attenuation of the reflected radiation can then be predicted.

IV. Application

Introduction

This chapter describes the use of the model in predicting the performance of camouflage netting from measurements made on indoor radar ranges. Equations developed in the previous chapter are implemented in FORTRAN code to generate attenuation data for purposes of comparison. Complex constitutive parameters are assumed, but procedures for determining actual parameters are discussed.

Parameter Measurement and Estimation

Effective net parameters required for this model include permittivity, ϵ, permeability, μ, and thickness, d. The development of ϵ and μ are complicated by their treatment as complex dyadic quantities, but they can be calculated from measurements on an indoor radar range. By treating them as two-dimensional symmetric dyads, they can be assembled from transmission or reflection measurements made at perpendicular and parallel polarizations. This approach is based on a two dimensional approach, as in Figure 1, with the deployed net symmetrical about the z axis.

The indoor radar range can be used to determine constitutive parameters of the net using inverse techniques. Such techniques can determine complex values for permittivity and permeability, as well as account for inhomogeneities in the net. These techniques develop the constitutive parameters by measuring the transmission or reflection coefficients of the material at specific points and solving simultaneous equations to determine the basic constitutive parameters of interest(24).

For a range set up to determine transmission coefficients, the parameters are calculated using the relation:

$$T = \frac{1}{\cos\delta + j\left(Z + \frac{1}{Z}\sin(\frac{\delta}{2})\right)} \tag{38}$$

$$\begin{array}{lrcl}
\text{where} & T & = & \text{Transmission coefficient} \\
& \delta & = & 2\pi\left(\frac{d}{\lambda}\right) I \\
& I & = & \mu_r\epsilon_r - \sin^2(\theta) \\
& Z_\perp & = & (\mu_r\cos\theta)/I \\
& Z_\parallel & = & I/(\epsilon_r\cos\theta) \\
& d & = & \text{thickness} \\
& \theta & = & \text{angle of incidence} \\
& \lambda & = & \text{wavelength} \\
& \epsilon & = & \text{complex permittivity, } \epsilon' + j\epsilon'' \\
& \mu & = & \text{complex permeability, } \mu' + j\mu''
\end{array} \qquad (24:18)$$

To determine real and imaginary components of ϵ and μ, the indoor radar range is set up to measure T at four angles of incidence. With the resulting four values of T, four simultaneous equations are obtained. Iterative techniques are used to calculate the four variables of interest: ϵ', ϵ'', μ', and μ''(24). The measurement and calculation of T at parallel and perpendicular polarizations requires the use of $Z_\perp$ or $Z_\parallel$ in equation 38. By obtaining values at both polarizations, the dyadic descriptions of ϵ and μ ($\underline{\underline{\epsilon}}$ and $\underline{\underline{\mu}}$) may be developed as addressed in Chapter 3.

Because the net is an inhomogeneous material, repeated measurements must be made. This technique assumes the material to be locally homogeneous, and measurements are made by focusing the incident beam on small portions of the material.

The thickness of the net material is another random variable which must be described. The radar scattering cloth is less than a millimeter thick, but when it is incised and fastened to the net, it drapes in such a way as to occupy a layer several centimeters thick. Although the garnished net occupies a thickened layer, the cloth

occupies only a small fraction of the layer's volume. For an incident beam hitting a segment of the cloth, the relative location of the cloth in the layer is largely irrelevant. The change in r_1 or even r_2 over the span of a few centimeters is insignificant and will have no appreciable effect on the results of equation 13. The orientation of the cloth will vary widely and serve to randomize the angle of incidence, θ_i. However, if the measurements of the constitutive parameters are made on incised cloth that is stretched and draped as in the fabricated nets, the random description of the constitutive parameters will include the randomness of the angle of incidence.

For purposes of this model, the thickness of the layer is assumed to be 0.5 cm, which is greater than the actual thickness of a single layer of the radar scattering cloth, but the effective thickness and the randomness of the orientation and location of the cloth in the net layer will be accounted for in the measured constitutive parameters of a continuous layer. Whatever the value of the chosen thickness, if the same value used in measuring the constitutive parameters is applied to the equations used to estimate the attenuation ratio, the specific value will be irrelevant, because the calculated constitutive parameters will be based on the assumed thickness.

Computer Implementation

The theoretical development of Chapter 3 can be implemented in computer programming languages. RATIO, TCOEFF, THETA and SIGMA are four examples. These FORTRAN programs are built around equation 37 and provide an estimate of the netting system's performance. Although other programming languages could be used, FORTRAN's ability to handle complex numbers in arrays makes it a natural choice for the dyadic descriptions needed. Outputs that follow are based on assumed values of constitutive parameters. Actual measurements of the key values can be substituted when available. The code for these programs is listed in Appendix B.

Programs RATIO and TCOEFF

The FORTRAN program RATIO is a general implementation of the equations in Chapter 3. It calculates the attenuation ratio as defined in equation 37 for given input parameters. It does this by calculating complex dyadic values of both the transmission and reflection coefficients. It can be used to determine the attenuation ratio for a variety of constitutive parameters. Sample output is included in Appendix B. The inputs are complex permittivity, complex permeability, net thickness, frequency and angle of incidence. By varying those parameters under the control of a hostile radar, namely the frequency and angle of incidence, the effectiveness of the netting material can be estimated. As with the program TCOEFF, more useful results can be obtained by using measured values for constitutive parameters.

A representative sample of transmission data measured by the Belvoir Research, Development and Evaluation Center is shown at Figure 6. The figure shows transmission loss versus frequency for a sample of radar scattering cloth hung so that a beam makes a single pass through the cloth at a fifteen degree angle of incidence. The sample consists of plain cloth with incisions according to the procurement specification. These incisions are then taped so that the cloth remained flat, rather than draping as on the fabricated net. It should be noted that vertical and horizontal incisions refer to orientation of incised cloth, not the polarization of the incident radiation.

Both sets of measured data show a general downward trend, demonstrating the material to be increasingly opaque at higher frequencies. The difference in slopes of the two sets of measured data may stem from several phenomena, which would arise solely from the orientation of the sample of cloth. Although the incisions in the cloth may be the source of the difference, this is doubtful, as the incisions are taped closed and any electrical breaks should be insignificant factors due to the low conductivity of the cloth. A more likely explanation lies in the way the scattering fibers are embedded in the cloth. The fibers are randomly oriented in the cloth, but the warp

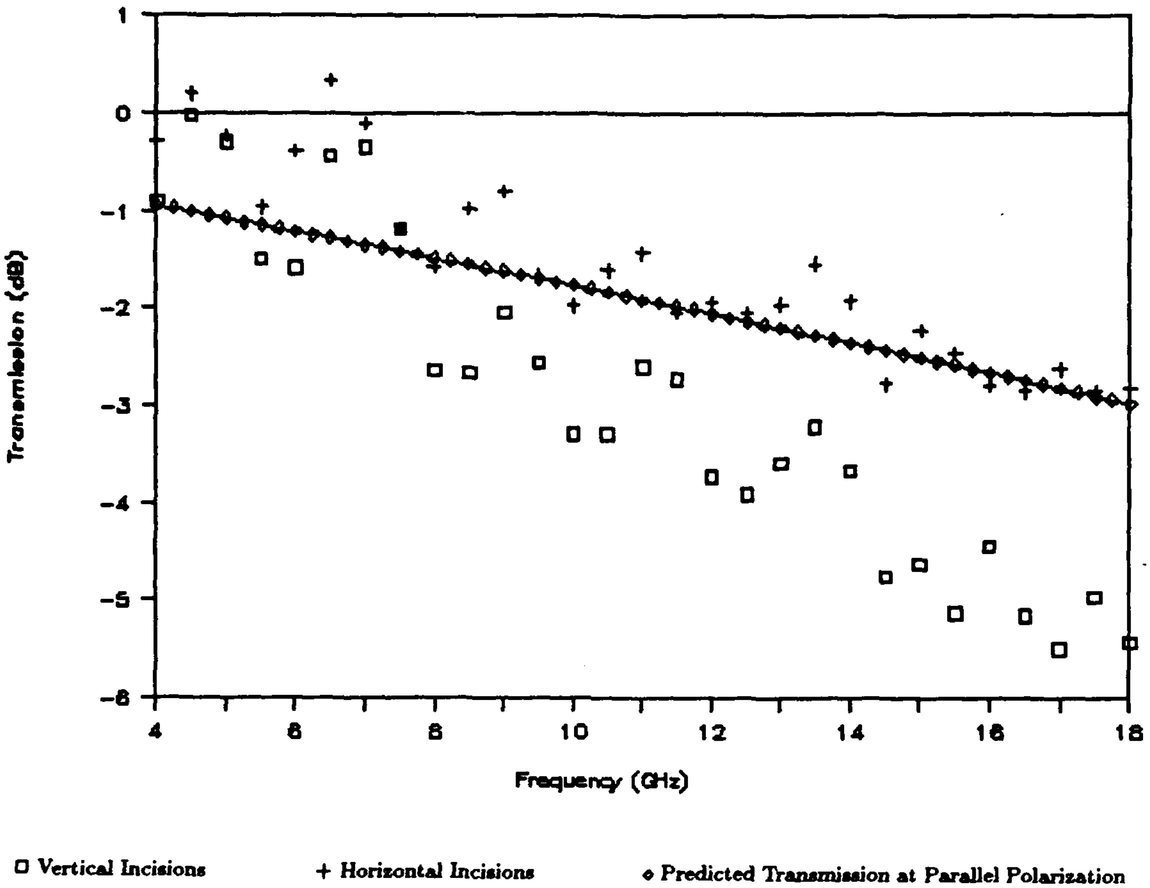

Figure 6. Measured and Calculated Transmission Data

and woof of the fabric may tend to accept the fibers with a bias in the orientation, or the manner in which they are applied to the fabric introduces such a bias. In either case the transmission properties at the microscopic level would be altered if the scattering fibers are not uniformly distributed in their random orientation.

The data presented in Figure 6 can be used to predict a value for ϵ'' using the program TCOEFF, which calculates the transmission coefficients of the netting for the same range of frequencies displayed in the figure. Data generated by the FORTRAN program TCOEFF is superimposed on the measured data in Figure 6 and confirms that as frequency increases, the material becomes more opaque to the

radiation. This data is generated using the following assumed values for constitutive parameters:

$$\begin{array}{lrcl}
\text{real relative permittivity,} & \epsilon' & = & 1.0 \\
\text{conductivity,} & \sigma & = & 0.7\ \mho\mathrm{m}^{-1} \\
\text{complex relative permeability,} & \mu' + j\mu'' & = & 1.0 + j0.0 \\
\text{net thickness,} & d & = & .5\ \mathrm{cm}
\end{array}$$

TCOEFF determines complex permittivity by assuming it to be

$$\epsilon = \epsilon' + j\epsilon'' \approx 1.0 + j\left(\beta + \frac{\sigma}{\omega\epsilon_0}\right) \tag{39}$$

where β is simply a variable to assist in curve fitting. The value of conductivity, σ, and thickness, d are assumed simply to provide data for Figure 6. The value of conductivity is an average characteristic of the layer, and is assumed solely as a mathematical construct to generate data. The thickness is arbitrarily chosen as previously discussed, and if consistent with the values used in the inverse measurement technique process, its specific value will not be relevant. The values of conductivity, σ, and the constant, β, used above were chosen for their curve fitting properties; their relation to the actual values of these parameters is purely a matter of conjecture.

The actual transmission coefficient, of course, will be better predicted with measured values for complex permittivity, ϵ' and ϵ''. Measured values of ϵ' and ϵ'' will vary with frequency, so repeated measurements on a range set up for inverse techniques are required. Similarly, the random orientation of the radar scattering cloth in the net will introduce a random variation in the angle of incidence, θ_i, so repeated measurements will be required to establish an ensemble average at each frequency.

Program THETA

Program THETA calculates the attenuation ratio for a range of aspect angles off normal from 0 to 90 degrees. An aspect angle of zero degrees represents normal

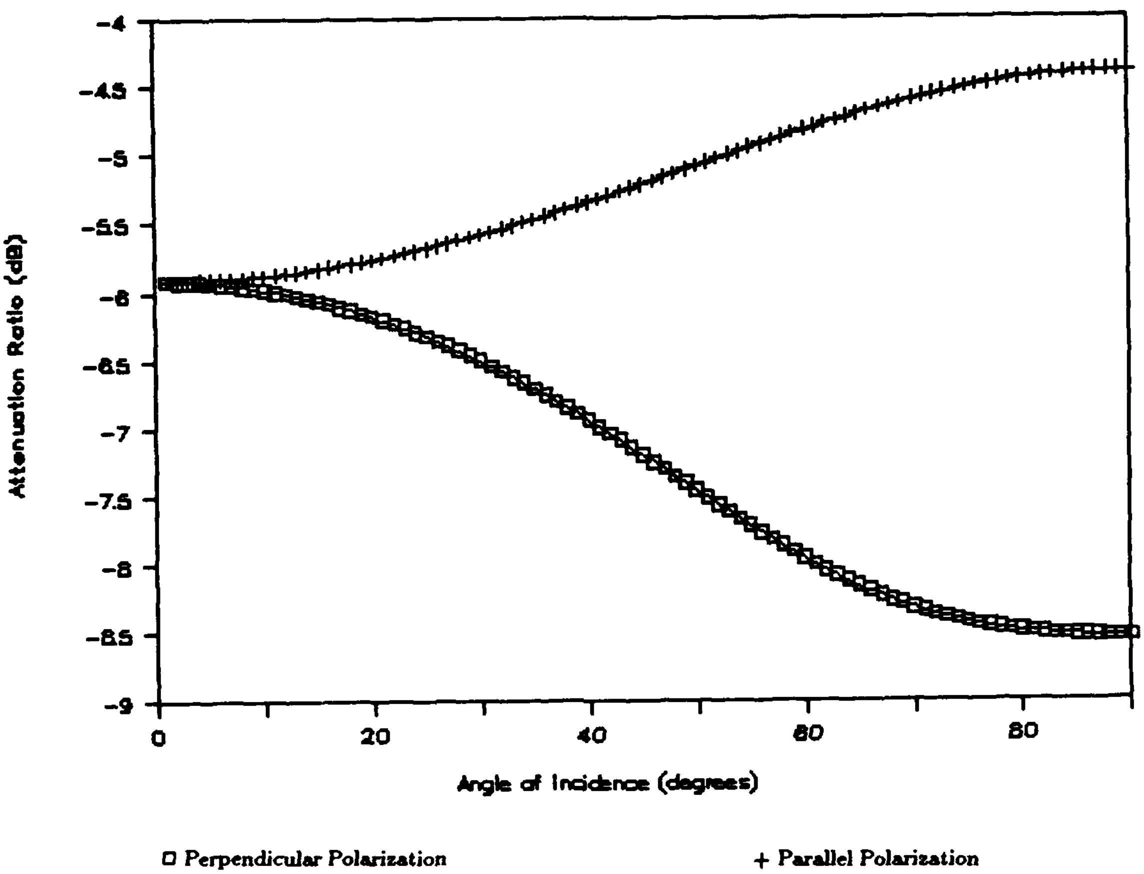

Figure 7. Attenuation Ratio vs. Angle of Incidence ($\epsilon'' = 0.88$)

incidence on the target. The concealed target has a radar cross section of unity. Although a target with a constant RCS is not likely to be deployed under a camouflage netting system, the output of this program shows the performance of the netting system alone. Figure 7 plots sample output data of THETA. This data is calculated for f = 10 GHz and r_2 = 1 m, using a value of $\epsilon'' = 0.88$ based on the estimated values of β and σ (conductivity) above. It also assumes values of h = 5m and R = 12.5m as shown in Figure 5.

Figure 7 shows the dependence of netting performance on the angle of incidence and polarization of the radiation. At normal incidence, this shows that an

attenuation of approximately −6 dB can be expected. This is not what one would intuitively expect. Greatest attenuation should occur at greater angles of incidence, where the effects of the multiple internal reflections shown in Figure 4 would occur. Although this does occur for parallel polarization, it is not true for perpendicular polarization.

For perpendicular polarization close to grazing angles, the net generally provides a greater reduction of the target's radar cross section, as expected.

Program SIGMA

Targets to be camouflaged do not have radar cross sections constant with respect to angle of incidence. Program SIGMA generates attenuation ratios based on a fluctuating target RCS. The target used in this program is a circular flat plate whose RCS is described by the equation

$$\sigma(\theta) = \frac{\lambda_0^2 k_0 a}{4\pi^2 \sin\theta}\left[\cos^2(2k_0 a \sin\theta) + \frac{\sin^2(2k_0 a \sin\theta)}{\sin^2\theta}\right] \tag{40}$$

where

σ = radar cross section

θ = angle of incidence (from horizontal)

λ = wavelength of incident radiation

k_0 = wave number of incident radiation

a = radius of plate

This equation is based on a physical optics approximation in the high frequency limit ($k_0 a \gg 1$) and is independent of polarization (20:513).

The radar cross section of a bare target and the same target concealed by a deployed camouflage netting system is shown in Figure 8. Although the physical optics RCS of the bare target is polarization independent, the attenuation due to the deployed camouflage net is not, so Figure 8 includes data for both parallel and perpendicularly polarized radiation incident on the net.

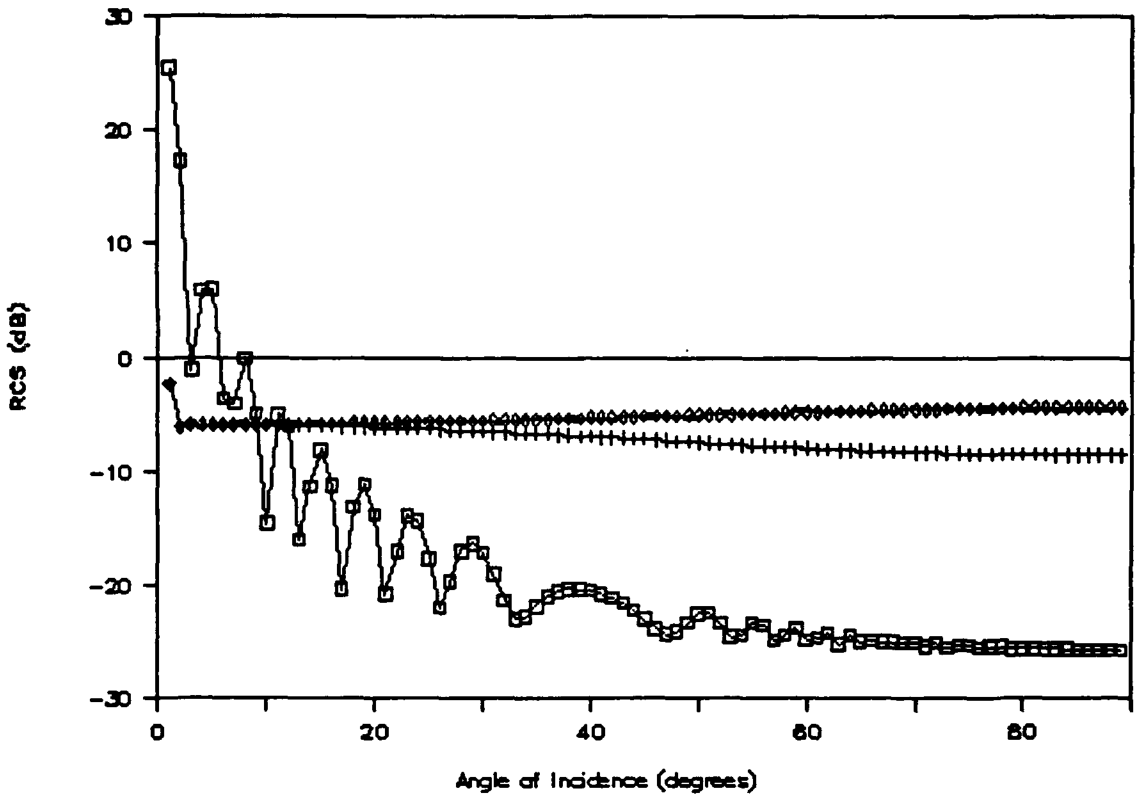

Figure 8. RCS Attenuation for Camouflaged Flat Plate ($\epsilon'' = 0.88$)

Compared to Figure 7, a similar pattern can be seen. Although the RCS of the target is now fluctuating with respect to aspect ratio, the curve of the attenuated RCS is virtually identical to the curve shown in Figure 7. In this case, the reflection from the net provides the dominant return from the camouflaged target. These curves, however, are generated from assumed data. If a lower value of ϵ'' is assumed, the reflection characteristics of the net are less dominant and the other mechanisms of attenuation become visible. Figure 9 shows the results of using a value of $\epsilon'' = 0.01$.

In this case, the perpendicularly polarized radiation is attenuated by the net across all angles of incidence, and at angles close to normal, the attenuated curve

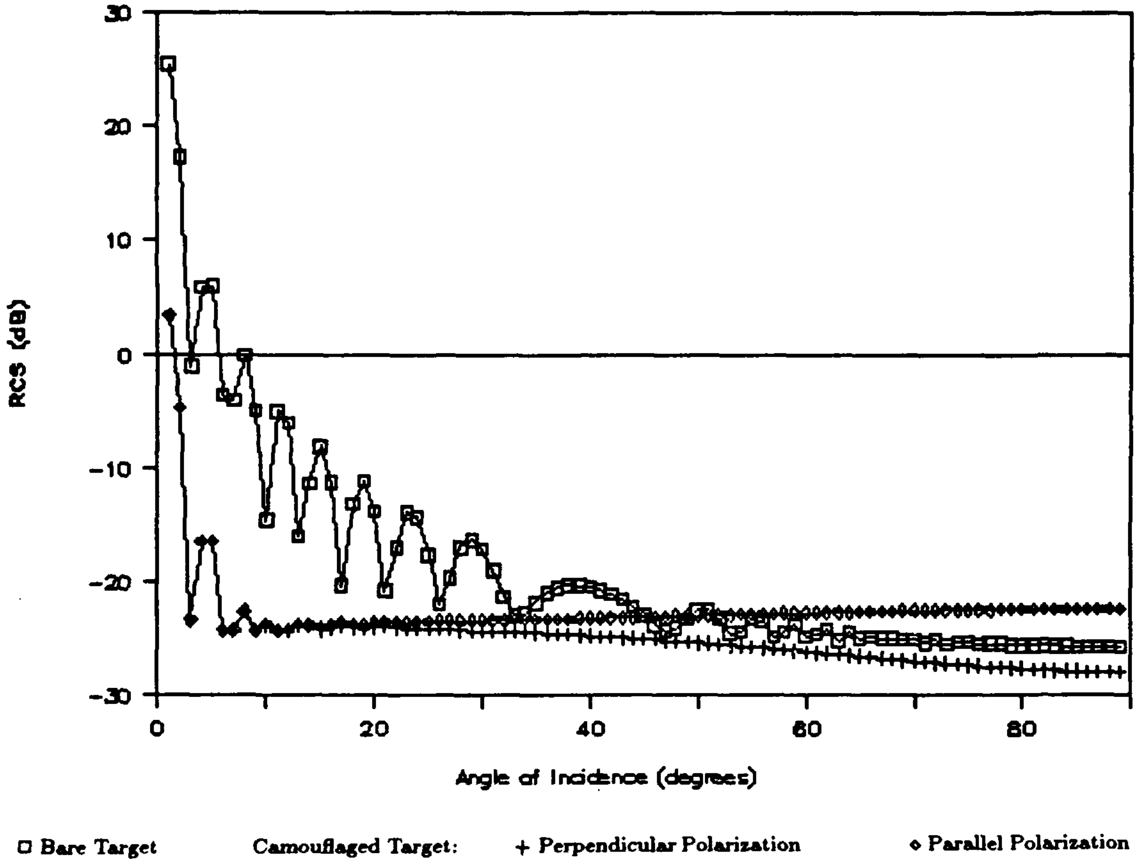

Figure 9. RCS Attenuation for Camouflaged Flat Plate ($\epsilon'' = 0.01$)

shows the fluctuation of the target's RCS. As with an $\epsilon'' = 0.88$, specific numerical values are not reliable, and measured values for ϵ'' should be used when available. The lower value of ϵ'' does however, show the attenuation effects of the net and underscores the importance of obtaining correct values for the constitutive parameters.

Conclusion

To apply this model, laboratory measurements should be geared toward obtaining the constitutive parameters ϵ', ϵ'', μ', and μ'' using inverse techniques. By taking measurements at both horizontal and vertical polarization, complex dyadic

descriptions will follow. From these measurements, the complex values of ϵ and μ can be formed, and the anticipated values of attenuation can be calculated.

The approximation is of infinite flat surface, albeit a locally flat one. Surface waves on an infinite plane may cause the dominance of the reflection term, however specific values should be used before adjustments are made. The actual deployment of the net will be as a zone of a sphere, or similar rounded shape. This will tend to lower the return by presenting a specular point to the illuminating radar, and scattering radiation away from the radar in surface wave mechanisms.

V. Conclusion

Conclusions

This study has shown that it is theoretically possible to predict the performance of a camouflage netting system based on parameters measurable in the laboratory. It must be noted, however, that attenuation of radar cross section is highly dependent on the angle of incidence of the radar wave and the constitutive parameters of the net. Prediction of attenuation must be tempered with cautions on fluctuations anticipated with variations in these variables.

Recomendations

Future efforts in the laboratory should be geared toward measuring the complex constitutive parameters of camouflage netting. With a reasonably accurate estimate of key variables, the validation of the model can be *attempted*. Although the descriptive parameters can be determined by inverse techniques, these techniques need to be adapted to meet the specific requirements of netting measurements. Specific areas include:

- A statistical description of the net with respect to its presence or absence in the path of a beam.
- A statistical description of the net's thickness.
- Development of code for calculation of complex parameters based on measurements at multiple frequencies as well as multiple angles of incidence.
- Construct target frame suitable for use at the Belvoir Research, Development and Evaluation Center's range facilities.
- Optimize antenna horn size to provide sufficiently narrow beamwidth at interface with net sample.

Once the physical plant necessary to measure the complex constitutive parameters is available, measurements must be taken with variations in incidence angles and frequencies. Variation of incidence angle will permit the prediction of perfomance at a wide range of potential radar look angles. Measurements at a wide range of frequencies, although anticipated to have a smaller effect, will provide data on anticipated performance at a wide range of threat radar frequencies. Variation of both frequencies and look angles should be geared toward anticipated threats.

With the parameters obtained from the laboratory, the techniques addressed in chapters three and four can then be applied and correlation with flyover data can be made.

Appendix A. *Camouflage Netting*

Introduction

This appendix consists of a brief description of the light weight camouflage screen system. The netting system is described with emphasis on its radar scattering properties.

Camouflage Netting System

The test system is the Army's currently deployed camouflage netting system, formally described as camouflage screen system, lightweight, radar scattering. It is available in woodland, desert or snow color schemes, the differences lying solely in the colors and incision patterns used in the camouflage garnishment. It is also available in radar transparent version, to provide visual camouflage for active radar equipment, yet not interfere with the radar's operation (11:1-2–1-7).

The camouflage system consists of hexagonal and rhombic shaped screen modules measuring 4.9 meters per side (12:4). These screens are designed to be fastened together in configurations large enough to conceal the desired vehicle, object or position. (11:1-7). The screen itself consists of a polyester fiber net garnished with colored radar scattering cloth which has been incised to resemble foliage. Each module is reversible, allowing the use of two color schemes (12:4).

The scattering properties of the radar scattering cloth are obtained by impregnating it with stainless steel filaments (11:1-12). Flat stock samples of the radar scattering cloth are specified to have a one-way transmission of not more than twenty percent and not less than ten percent at frequencies of 6, 10, 17, and 35 GHz. The fabricated screen will have a one-way transmission attenuation of not less than 3 dB at the same frequencies. To account for the random nature of the garnishment, testing of the fabricated screen is to be done in a raster fashion, by moving the screen

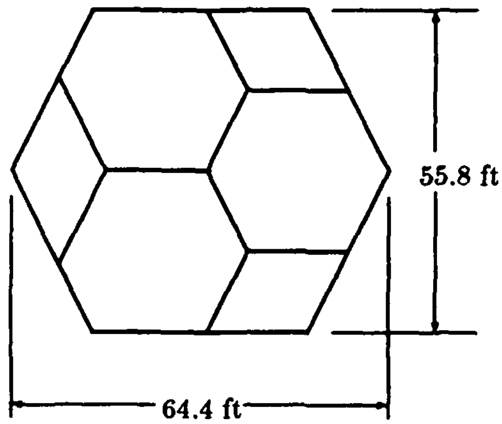

Figure 10. Net Configuration for Concealing a Tank

through the radar beam and averaging the signal over the entire area of the screen (12:6,21).

Deployment of Screen

To conceal a given vehicle, the appropriate number of modules are fastened together. For example, to conceal a tank, three sets of hexagonal and rhombic modules are required in the configuration shown in figure 10 (11:1-14).

The assembled screen is spread over the vehicle and staked to the ground at the corners to provide complete cover. The net is then raised off of the vehicle using aluminum, or more recently, fiberglass poles with a batten spreader assembly so that the net is at least 2 ft away from the vehicles at all points (11:2-4–2-11).

Appendix B. *Computer Code*

Introduction

This appendix contains the computer codes used to generate data presented in chapter 4. The programs are written in FORTRAN and compiled using *Microsoft* FORTRAN Optimizing Compiler, version 4.0.

Program RATIO *Listing*

```
C                       PROGRAM RATIO


C************************************************************
C
C    This program is designed to predict the attenuation
C    of the radar cross section of a target due to the
C    deployment of a camouflage netting system.  It does
C    this by calculating complex transmission and
C    reflection dyads, given complex constitutive
C    parameters.  Output data are echoed to the screen
C    and saved in the file RATIO.DAT
C
C    Parenthetical numbers in comment statements refer
C    to equation numbers in the body of the thesis.
C
C************************************************************
C
C    Constants used:
C
C     EPO     = permittivitty of free space
C     MUO     = permeability  of free space
C     I       = square root of -1
C     PI      = 3.14...
C     IDYAD   = Identity dyad
C    Input data
C     F       = frequency of incident radiation (GHz)
C     W       = angular frequency of incident radiation
C     D       = thickness of net
C     THETAI  = incidence angle of incoming radiation
```

```
C     R2      = distance separating net and target
C     SIGMA   = radar cross section of target
C     EPR,EPI = real and imaginary relative permittivity
C     MUR,MUI = real and imaginary relative permeability
C    Calculated variables
C     THETAN  = path angle of radiation in net
C     EPN     = permittivitty of net material
C     MUN     = permeability  of net material
C     KN      = wave number of net
C     KO      = wave number of free space
C     Z       = complex impedance
C     R       = Reflection coefficient
C     T       = Transmission coefficient
C     ALPHA   = Attenuation angle
C     ATNRAT  = Dyadic attenuation ratio
C     PERPDB  = Attenuation ratio at perpendicular polarization
C     PARDB   = Attenuation ratio at parallel polarization
C
C     The following are simply used as intermediate
C      variables in the calculation of one or more
C      of the above:
C
C     AASIN, TANA, SIGMA2, C, DET
C
C************************************************************


C    Housekeeping details

      REAL EPR,EPI,EPO
      REAL MUR,MUI,MUO,KO
      COMPLEX EPN,MUN,KN,AASIN,THETAN,ALPHA
      DIMENSION Z(2,2),R(2,2),T(2,2),C(2,2)
      DIMENSION IDYAD(2,2),ATNRAT(2,2)
      COMPLEX Z,TANA,R,T,I,ATNRAT,IDYAD,C,DET
      OPEN(1,STATUS='NEW',FILE='RATIO.DAT')

C    Establish constants

      PI=3.141592624
      EPO=1E-9/(36*PI)
      MUO=400*PI*1E-9
```

```
      I=CMPLX(0.0,1.0)

C************************************************************
C
C    Read in measurable variables and adjust units.
C
C************************************************************

      WRITE (*,001)
      WRITE (1,001)
  001 FORMAT(/,1X,'Calculation of Complex Fresnel Coefficients',//)
      WRITE (*,101)
  101 FORMAT(1X,'Please enter frequency in GHz:',I2)
      READ (*,102) F
  102 FORMAT(F8.2)
      WRITE (*,105)
  105 FORMAT(1X,'Please enter net thickness in cm:',I2)
      READ (*,106) D
  106 FORMAT(F8.3)
      WRITE (*,108)
  108 FORMAT(1X,'Please enter Angle of Incidence in degrees:',I2)
      READ (*,110) THETAI
  110 FORMAT(F8.2)

C    Read in complex relative permittivity

      WRITE (*,112)
  112 FORMAT(1X,'Please enter complex permittivity:',I2)
      WRITE (*,114)
  114 FORMAT(5x,'Real part:',I2)
      READ (*,115) EPR
  115 FORMAT(F8.0)
      WRITE (*,116)
  116 FORMAT(5x,'Imaginary part:',I2)
      READ (*,117) EPI
  117 FORMAT(F8.0)

C    Read in complex relative permeability

      WRITE (*,122)
  122 FORMAT(1X,'Please enter complex permeability:',I2)
      WRITE (*,124)
```

```
  124 FORMAT(5x,'Real part:',I2)
      READ (*,125) MUR
  125 FORMAT(F8.0)
      WRITE (*,126)
  126 FORMAT(5x,'Imaginary part:',I2)
      READ (*,127) MUI
  127 FORMAT(F8.0)

C    Adjust units and form complex parameters

      D=D/100.0
      F=F*1E9
      W=2*PI*F
      THETAI=THETAI*PI/180.0
      EPN=CMPLX(EPR,EPI)*CMPLX(EP0,0.0)
      MUN=CMPLX(MUR,MUI)*CMPLX(MU0,0.0)

C************************************************************
C
C    Recap input data to screen and file
C
C************************************************************

      WRITE (*,128)
      WRITE (1,128)
  128 FORMAT(1X,'Recap of input data:',I2)
      WRITE (*,129) F,D,THETAI,EPN,MUN
      WRITE (1,129) F,D,THETAI,EPN,MUN
  129 FORMAT(1X,'frequency     =',E10.3,' Hz'/,1X,'thickness     =',F10.
     .5,' meters'/,1X,'angle of inc  =',F10.3,' radians'/,1X'epsilon
     .    =',E10.3,'+ j',E10.3,' Farads/meter'/,1X'mu            =',E10.3
     .,'+ j',E10.3,' Henrys/meter',/)
      WRITE (*,130) EPR,EPI,MUR,MUI
      WRITE (1,130) EPR,EPI,MUR,MUI
  130 FORMAT(1X,'epsilon (rel) =',F7.3,'+ j',F7.3,/,1X,'mu      (rel) ='
     .,F7.3,'+ j',F7.3,/)

C************************************************************
C
C    Calculate intermediate variables
C
C************************************************************
```

```
C    Calculate Complex wave numbers
      K0=W*SQRT(EP0*MU0)
      KN=W*CSQRT(EPN*MUN)
      AASIN=CSIN(CMPLX(THETAI,0.0))*(KN/K0)
C   Determine thetaN (complex arcsin of AASIN)                   (eqn 22)
      THETAN=CMPLX(0.0,-1.0)*CLOG(I*AASIN+CSQRT(CMPLX(1.0,0.0)-AASIN**2)
     .)

C   Echo computed data to screen
      WRITE (*,131)
      WRITE (1,131)
  131 FORMAT(1X,'Calculated  data:',I2)
      WRITE (*,132) W,K0,KN,THETAN
      WRITE (1,132) W,K0,KN,THETAN
  132 FORMAT(1X,'W      =',E10.3,' radians/sec',/1X,'K0      =',E10.3,/1X
     .,'KN      =',E10.3,'+ j',E10.3,/1X,'THETAN =',E10.3,'+ j',E10.3,/)

C************************************************************
C
C    Calculate Complex impedances                 (eqn 18,19,20)
C
C    Complex impedances, and transmission and reflection
C      coefficients are in the form  are in the form:
C      Z(p,m), R(p,m), and T(p,m), respectively.
C      where the first dimension, p, denotes the polarization:
C              (1=perpendicular or 2=parallel)
C      and the second, m, denotes the medium:
C                  (1=air and 2=the net)
C
C************************************************************

      Z(1,1)=CMPLX((1/COS(THETAI))*(SQRT(MU0/EP0)),0.0)
      Z(1,2)=(CMPLX(1.0,0.0)/CCOS(THETAN))*(CSQRT(MUN/EPN))
      Z(2,1)=CMPLX((COS(THETAI))*(SQRT(MU0/EP0)),0.0)
      Z(2,2)=(CCOS(THETAN))*(CSQRT(MUN/EPN))
      ALPHA=((CMPLX(K0,0.0))/KN)**2*CMPLX((SIN(THETAI)**2),0.0)
      ALPHA=KN*CMPLX(D,0.0)*(CSQRT(CMPLX(1.0,0.0)-ALPHA))

C    Echo Complex impedances to screen
      WRITE (*,201)
      WRITE (1,201)
```

```
  201 FORMAT(1X,'Complex impedances,  z(polarization,medium) :',I2)
      DO 215, M=1,2
      WRITE (*,210) Z(M,1),Z(M,2)
      WRITE (1,210) Z(M,1),Z(M,2)
  210 FORMAT(1X,E10.3,'+ j',E10.3,5X,E10.3,'+ j',E10.3)
  215 CONTINUE

C************************************************************
C
C    Calculate Fresnel coefficients
C
C************************************************************

C    Calculate the complex tangent of alpha
      TANA=CSIN(ALPHA)/CCOS(ALPHA)
      DO 250 M=1,2
C    Calculate reflection coefficient                          (eqn 23)
      R(M,M)=(I*(Z(M,1)**2-Z(M,2)**2)*TANA)/((CMPLX(2.0,0.0)*Z(M,1)*Z(M,
     .2))-I*(Z(M,1)**2+Z(M,2)**2)*TANA)
C    Calculate transmission coefficient                        (eqn 24)
      T(M,M)=(CMPLX(2.0,0.0)*Z(M,1)*Z(M,2))/(CMPLX(2.0,0.0)*Z(M,1)*Z(M,2
     .)*CCOS(ALPHA)-I*(Z(M,1)**2+Z(M,2)**2)*CSIN(ALPHA))
  250 CONTINUE
      R(1,2)=CMPLX(0.0,0.0)
      R(2,1)=CMPLX(0.0,0.0)
      T(1,2)=CMPLX(0.0,0.0)
      T(2,1)=CMPLX(0.0,0.0)

C************************************************************
C
C    Write Fresnel Coefficients screen and file
C
C************************************************************

      WRITE (*,252)
      WRITE (1,252)
  252 FORMAT(/,1X,'Reflection coefficients, R(polarization,medium) :',I2
     .)
      DO 257, L=1,2
      WRITE (*,255) R(L,1),R(L,2)
      WRITE (1,255) R(L,1),R(L,2)
  255 FORMAT(1X,E10.3,'+ j',E10.3,5X,E10.3,'+ j',E10.3)
```

```
  257 CONTINUE

      WRITE (*,262)
      WRITE (1,262)
  262 FORMAT(/,1X,'Transmission coefficients, T(polarization,medium):',I
     .2)
      DO 267, N=1,2
      WRITE (*,265) T(N,1),T(N,2)
      WRITE (1,265) T(N,1),T(N,2)
  265 FORMAT(1X,E10.3,'+ j',E10.3,5X,E10.3,'+ j',E10.3)
  267 CONTINUE

C************************************************************
C
C     Calculate attenuation Ratio                        (eqn 36)
C
C************************************************************

C     Establish Constants
C      arbitrary values are used for SIGMA and R2. Specific
C      values can be substituted or read in as previously
C      used parameters were.
      SIGMA=1.0
      R2=1.0
      IDYAD(1,1)=CMPLX(1.0,0.0)
      IDYAD(1,2)=CMPLX(0.0,0.0)
      IDYAD(2,1)=CMPLX(0.0,0.0)
      IDYAD(2,2)=CMPLX(1.0,0.0)
      SIGMA2=SIGMA/(4.0*PI*R2**2)**2

C     Multiply matrix by a constant

      DO 270, K=1,2
      DO 275, J=1,2
      ATNRAT(K,J)=R(K,J)*CMPLX(SIGMA2,0.0)
  275 CONTINUE
  270 CONTINUE

      DO 300, K=1,2
      DO 310, J=1,2
      ATNRAT(K,J)=IDYAD(K,J)-ATNRAT(K,J)
  310 CONTINUE
```

```
  300 CONTINUE

C     Invert matrix

      DET=ATNRAT(1,1)*ATNRAT(2,2)-ATNRAT(1,2)*ATNRAT(2,1)
      C(1,1)=ATNRAT(2,2)/DET
      C(1,2)=CMPLX(-1.0,0)*ATNRAT(1,2)/DET
      C(2,1)=CMPLX(-1.0,0)*ATNRAT(2,1)/DET
      C(2,2)=ATNRAT(1,1)/DET

C     Multiply matrix

      DO 320 K=1,2
      DO 330 J=1,2
      ATNRAT(K,J)=C(K,1)*T(1,J)+C(K,2)*T(2,J)
  330 CONTINUE
  320 CONTINUE

C     Multiply matrix

      DO 340 K=1,2
      DO 350 J=1,2
      C(K,J)=T(K,1)*ATNRAT(1,J)+T(K,2)*ATNRAT(2,J)
  350 CONTINUE
  340 CONTINUE

C     Multiply matrix by a constant

      DO 360 K=1,2
      DO 370 J=1,2
      ATNRAT(K,J)=C(K,J)*CMPLX(SIGMA2,0.0)
  370 CONTINUE
  360 CONTINUE

C     Add matrix and multiply by a constant

      DO 380, K=1,2
      DO 390, J=1,2
      ATNRAT(K,J)=(R(K,J)+ATNRAT(K,J))/CMPLX(SIGMA,0.0)
  390 CONTINUE
  380 CONTINUE
```

```
C**********************************************************
C
C    Write Attenuation Ratio to Screen and File
C
C**********************************************************

      WRITE (*,400)
      WRITE (1,400)
  400 FORMAT(/,17X,'Attenuation Ratio',/,I2)

      WRITE (*,500)ATNRAT(1,1),ATNRAT(1,2)
      WRITE (1,500)ATNRAT(1,1),ATNRAT(1,2)
  500 FORMAT(2(5X,F8.5,'+j',F8.5))
      WRITE (*,500)ATNRAT(2,1),ATNRAT(2,2)
      WRITE (1,500)ATNRAT(2,1),ATNRAT(2,2)

      PERPDB=LOG10(CABS(ATNRAT(1,1)))*10.0
      PARDB=LOG10(CABS(ATNRAT(2,2)))*10.0

      WRITE (*,510)
      WRITE (1,510)
  510 FORMAT(//,6X,'Attenuation Ratio')
      WRITE (*,515)
      WRITE (1,515)
  515 FORMAT(8X,'polarization')
      WRITE (*,520)
      WRITE (1,520)
  520 FORMAT(3X,'perpendicular   parallel')

      WRITE (*,550)PERPDB,PARDB
      WRITE (1,550)PERPDB,PARDB
  550 FORMAT(F12.3,F12.3,/)

      CLOSE(UNIT=1)

      STOP
      END
```

Typical RATIO *Output Data*

```
Calculation of Complex Fresnel Coefficients

Recap of input data:
frequency     =  .100E+11 Hz
thickness     =    .00500 meters
angle of inc  =      .262 radians
epsilon       =  .884E-11+ j  .778E-11 Farads/meter
mu            =  .126E-05+ j  .000E+00 Henrys/meter

epsilon (rel) =  1.000+ j   .880
mu      (rel) =  1.000+ j   .000

Calculated  data:
W      =  .628E+11 radians/sec
KO     =  .209E+03
KN     =  .226E+03+ j  .853E+02
THETAN =  .282E+00+ j  .110E+00

Complex impedances,  z(polarization,medium) :
  .390E+03+ j  .000E+00       .320E+03+ j -.109E+03
  .364E+03+ j  .000E+00       .292E+03+ j -.121E+03

Reflection coefficients, R(polarization,medium) :
 -.150E+00+ j -.179E+00       .000E+00+ j  .000E+00
  .000E+00+ j  .000E+00      -.162E+00+ j -.218E+00

Transmission coefficients, T(polarization,medium):
  .319E+00+ j  .575E+00       .000E+00+ j  .000E+00
  .000E+00+ j  .000E+00       .328E+00+ j  .580E+00

                Attenuation Ratio

     -.15120+j -.17633       .00000+j  .00000
      .00000+j  .00000      -.16369+j -.21593

     Attenuation Ratio
       polarization
  perpendicular   parallel
     -6.340       -5.671
```

Program TCOEFF *Listing*

```
C                         PROGRAM TCOEFF


C************************************************************
C
C    This program is designed to calculate complex
C    transmission coefficients over a range of frequencies,
C    from constitutive parameters entered at screen prompts.
C    It is designed to be used to compare the attenuation
C    model with measured attenuation by camouflage netting
C    materials. Output data are written to the screen and to
C    the file TRANS.DAT.
C
C    Parenthetical numbers in comment statements refer
C    to equation numbers in the body of the thesis.
C
C************************************************************
C
C    Constants used:
C
C     EPO     = permittivitty of free space
C     MUO     = permeability  of free space
C     I       = square root of -1
C     PI      = 3.14...
C     F       = frequency of incident radiation (GHz)
C     W       = angular frequency of incident radiation
C     D       = thickness of net
C     SIGMA   = conductivity
C     THETAI  = incidence angle of incoming radiation
C     THETAN  = path angle of radiation in net
C     EPN     = permittivitty of net material
C     MUN     = permeability  of net material
C     KN      = wave number of net
C     KO      = wave number of free space
C     Z       = complex impedance
C     R       = Reflection coefficient
C     T       = Transmission coefficient
C     ALPHA   = Attenuation angle
C
C     The following are simply used as intermediate
C      variables in the calculation of one or more
```

```
C       of the above:
C
C      EPR, EPI, MUR, MUI, AASIN, TANA
C
C
C************************************************************

C     Housekeeping details

      REAL EPR,EPI,EPO
      REAL MUR,MUI,MUO,KO
      COMPLEX EPN,MUN,KN,AASIN,THETAN,ALPHA
      DIMENSION Z(2,2),R(2,2),T(2,2)
      COMPLEX Z,TANA,R,T,I
      OPEN(5,STATUS='NEW',FILE='trans.DAT')

C     Establish constants

      PI=3.141592624
      EPO=1E-9/(36*PI)
      MUO=400*PI*1E-9
      I=CMPLX(0.0,1.0)

C************************************************************
C
C     Read in measurable variables and adjust units.
C
C************************************************************


      WRITE (*,10)
   10 FORMAT(1X,'Enter constant beta:',I2)
      READ (*,12) BETA
   12 FORMAT(F8.4)
      WRITE (*,101)
  101 FORMAT(1X,'Please enter conductivity, sigma:',I2)
      READ (*,102) sigma
  102 FORMAT(F8.4)
      WRITE (*,105)
  105 FORMAT(1X,'Please enter net thickness in cm:',I2)
      READ (*,106) D
  106 FORMAT(F8.3)
```

```
C     Initialize frequency
      F=4.0

      D=D/100.0
      THETAI=15.0*PI/180.0

C    Read in complex relative permittivity

      WRITE (*,112)
  112 FORMAT(1X,'Please enter complex permittivity:',I2)
      WRITE (*,114)
  114 FORMAT(5x,'Real part:',I2)
      READ (*,115) EPR
  115 FORMAT(F8.3)

C    Read in complex relative permeability

      WRITE (*,122)
  122 FORMAT(1X,'Please enter complex permeability:',I2)
      WRITE (*,124)
  124 FORMAT(5x,'Real part:',I2)
      READ (*,125) MUR
  125 FORMAT(F8.3)
      WRITE (*,126)
  126 FORMAT(5x,'Imaginary part:',I2)
      READ (*,127) MUI
  127 FORMAT(F8.3)

      MUN=CMPLX(MUR,MUI)*CMPLX(MU0,0.0)

      WRITE (*,005)
      WRITE (5,005)
  005 FORMAT(/,2X,'Freq',15X,'T  Perpendicular',20X,'T parallel')

      WRITE (*,006)
      WRITE (5,006)
  006 FORMAT(17X,'real',5X,'imaginary',5X,'dB',11X,'real',5X,'imaginary'
     .,5X,'dB'/)

C    Loop through range of frequencies: 4.0 - 18.0 GHz
```

```
      DO 600 J=1,57

C    Calculate angular frequency
      W=2*PI*F*1E9
      EPI=beta+SIGMA/(W*EP0)
      EPN=CMPLX(EPR,EPI)*CMPLX(EP0,0.0)

C    Calculate Complex wave numbers
      K0=W*SQRT(EP0*MU0)
      KN=W*CSQRT(EPN*MUN)
      AASIN=CSIN(CMPLX(THETAI,0.0))*(KN/K0)
C   Determine complex arcsin of AASIN
      THETAN=CMPLX(0.0,-1.0)*CLOG(I*AASIN+CSQRT(CMPLX(1.0,0.0)-AASIN**2)
     .)

C************************************************************
C
C    Calculate Complex impedances
C
C    Complex impedances, and transmission and reflection
C      coefficients are in the form  are in the form:
C      Z(p,m), R(p,m), and T(p,m), respectively.
C      where the first dimension, p, denotes the polarization:
C               (1=perpendicular or 2=parallel)
C      and the second, m, denotes the medium:
C                   (1=air and 2=the net)
C
C************************************************************

      Z(1,1)=CMPLX((1/COS(THETAI))*(SQRT(MU0/EP0)),0.0)
      Z(1,2)=(1/CCOS(THETAN))*(CSQRT(MUN/EPN))
      Z(2,1)=CMPLX((COS(THETAI))*(SQRT(MU0/EP0)),0.0)
      Z(2,2)=(CCOS(THETAN))*(CSQRT(MUN/EPN))
      ALPHA=((CMPLX(K0,0.0))/KN)**2*CMPLX((SIN(THETAI)**2),0.0)
      ALPHA=KN*CMPLX(D,0.0)*(CSQRT(CMPLX(1.0,0.0)-ALPHA))

C    Calculate Fresnel coefficients

C    Calculate the complex tangent of alpha
      TANA=CSIN(ALPHA)/CCOS(ALPHA)
C    Calculate transmission coefficient     (eqn 24)
      T(1,1)=(CMPLX(2.0,0.0)*Z(1,1)*Z(1,2))/(CMPLX(2.0,0.0)*Z(1,1)*Z(1,2
```

```
    .)*CCOS(ALPHA)-I*(Z(1,1)**2+Z(1,2)**2)*CSIN(ALPHA))
     T(2,2)=(CMPLX(2.0,0.0)*Z(2,1)*Z(2,2))/(CMPLX(2.0,0.0)*Z(2,1)*Z(2,2
    .)*CCOS(ALPHA)-I*(Z(2,1)**2+Z(2,2)**2)*CSIN(ALPHA))
     T(1,2)=CMPLX(0.0,0.0)
     T(2,1)=CMPLX(0.0,0.0)

     DB1=10.0*LOG10(cabs(T(1,1)))
     DB2=10.0*LOG10(cabs(T(2,2)))

     WRITE (*,261) F,T(1,1),DB1,T(2,2),DB2
     WRITE (5,261) F,T(1,1),DB1,T(2,2),DB2
 261 FORMAT(F7.2,2(5X,E10.3,2X,E10.3,2X,F7.2),I2)

     F=F+0.25
 600 CONTINUE

     CLOSE(UNIT=5)

     STOP
     END
```

Program THETA *Listing*

```
C                         PROGRAM THETA


C***********************************************************
C
C    This program is designed to predict the attenuation
C    of the radar cross section of a target at angles of
C    incidence from 0 to 90 degrees due to the deployment
C    of a camouflage netting system.  It does this
C    by calculating complex transmission and reflection
C    dyads, given complex constitutive parameters.
C    Output data are echoed to the screen and saved
C    in the file THETA.DAT
C
C    Parenthetical numbers in comment statements refer
C    to equation numbers in the body of the thesis.
C
```

```
C***********************************************************
C
C    Constants used:
C
C     EPO     = permittivitty of free space
C     MUO     = permeability  of free space
C     I       = square root of -1
C     PI      = 3.14...
C     IDYAD   = Identity dyad
C     F       = frequency of incident radiation (GHz)
C     W       = angular frequency of incident radiation
C     D       = thickness of net
C     THETAI  = incidence angle of radiation on target
C     R2      = distance separating net and target
C     SIGMA   = radar cross section of target
C    Calculated variables
C     THETAN  = path angle of radiation in net
C     THENET  = incidence angle of radiation on net
C     EPN     = permittivitty of net material
C     MUN     = permeability  of net material
C     KN      = wave number of net
C     KO      = wave number of free space
C     Z       = complex impedance
C     R       = Reflection coefficient
C     T       = Transmission coefficient
C     ALPHA   = Attenuation angle
C     ATNRAT  = Dyadic attenuation ratio
C
C     The following are simply used as intermediate
C      variables in the calculation of one or more
C      of the above:
C
C     EPR, EPI, MUR, MUI, AASIN, TANA, SIGMA2, C, DET
C
C***********************************************************


C    Housekeeping details

      REAL THETAI,THETAR
      REAL EPR,EPI,EPO
      REAL MUR,MUI,MUO,KO
```

```
      COMPLEX EPN,MUN,KN,AASIN,THETAN,ALPHA
      DIMENSION Z(2,2),R(2,2),T(2,2),C(2,2)
      DIMENSION IDYAD(2,2),ATNRAT(2,2)
      COMPLEX Z,TANA,R,T,I,ATNRAT,IDYAD,C,DET
      OPEN(1,STATUS='NEW',FILE='THETA.DAT')

C    Establish constants

      PI=3.141592624
      EP0=1E-9/(36*PI)
      MU0=400*PI*1E-9
      I=CMPLX(0.0,1.0)

C************************************************************
C
C    Read in measurable variables and adjust units.
C
C************************************************************

      F=10.0
      D=0.5
      EPR=1.0
      EPI=0.88
      MUR=1.0
      MUI=0.0

C    Calculate angular frequency
      F=F*1E9
      W=2*PI*F

C    Adjust units and form complex parameters

      D=D/100.0
      EPN=CMPLX(EPR,EPI)*CMPLX(EP0,0.0)
      MUN=CMPLX(MUR,MUI)*CMPLX(MU0,0.0)

C************************************************************
C
C    Recap input data to screen and file
C
C************************************************************
```

```
      WRITE (*,128)
      WRITE (1,128)
  128 FORMAT(1X,'Recap of input data:',I2)
      WRITE (*,129) F,D,EPN,MUN
      WRITE (1,129) F,D,EPN,MUN
  129 FORMAT(1X,'frequency   =',E10.3,' Hz'/,1X,'thickness   =',F10.5,'
     .meters'/,1X,'epsilon     =',E10.3,'+ j',E10.3,' Farads/meter'/,1X,
     .'mu          =',E10.3,'+ j',E10.3,' Henrys/meter',//)

      WRITE (*,200)
      WRITE (1,200)
  200 FORMAT(//,11X,'Attenuation Ratio (dB)')
      WRITE (*,215)
      WRITE (1,215)
  215 FORMAT(5X,'angle of',9X,'polarization:')
      WRITE (*,220)
      WRITE (1,220)
  220 FORMAT(4x,'incidence',2x,'perpendicular   parallel')

C    Begin loop for aspect angles

      DO 700, M=1,90

C************************************************************
C
C    Calculate intermediate variables
C
C************************************************************

      THETAI=REAL(M)
      THETAR=THETAI*PI/180.0
      THENET=ASIN(7.5/12.5*SIN(THETAR))

C    Calculate Complex wave numbers
      KO=W*SQRT(EPO*MUO)
      KN=W*CSQRT(EPN*MUN)
      AASIN=CSIN(CMPLX(THENET,0.0))*(KN/KO)
C   Determine thetaN (complex arcsin of AASIN)                (eqn 22)
      THETAN=CMPLX(0.0,-1.0)*CLOG(I*AASIN+CSQRT(CMPLX(1.0,0.0)-AASIN**2)
     .)

C************************************************************
```

```
C
C    Calculate Complex impedances           (eqn 18,19,20)
C
C
C    Complex impedances, and transmission and reflection
C      coefficients are in the form  are in the form:
C      Z(p,m), R(p,m), and T(p,m), respectively.
C      where the first dimension, p, denotes the polarization:
C              (1=perpendicular or 2=parallel)
C      and the second, m, denotes the medium:
C                  (1=air and 2=the net)
C
C**********************************************************

      Z(1,1)=CMPLX((1/COS(THENET))*(SQRT(MU0/EP0)),0.0)
      Z(1,2)=(CMPLX(1.0,0.0)/CCOS(THETAN))*(CSQRT(MUN/EPN))
      Z(2,1)=CMPLX((COS(THENET))*(SQRT(MU0/EP0)),0.0)
      Z(2,2)=(CCOS(THETAN))*(CSQRT(MUN/EPN))
      ALPHA=((CMPLX(K0,0.0))/KN)**2*CMPLX((SIN(THENET)**2),0.0)
      ALPHA=KN*CMPLX(D,0.0)*(CSQRT(CMPLX(1.0,0.0)-ALPHA))

C**********************************************************
C
C    Calculate Fresnel coefficients
C
C**********************************************************

C    Calculate the complex tangent of alpha
      TANA=CSIN(ALPHA)/CCOS(ALPHA)
      DO 250 L=1,2
C    Calculate reflection coefficient                        (eqn 23)
      R(L,L)=(I*(Z(L,1)**2-Z(L,2)**2)*TANA)/((CMPLX(2.0,0.0)*Z(L,1)*Z(L,
     .2))-I*(Z(L,1)**2+Z(L,2)**2)*TANA)
C    Calculate transmission coefficient                      (eqn 24)
      T(L,L)=(CMPLX(2.0,0.0)*Z(L,1)*Z(L,2))/(CMPLX(2.0,0.0)*Z(L,1)*Z(L,2
     .)*CCOS(ALPHA)-I*(Z(L,1)**2+Z(L,2)**2)*CSIN(ALPHA))
  250 CONTINUE
      R(1,2)=CMPLX(0.0,0.0)
      R(2,1)=CMPLX(0.0,0.0)
      T(1,2)=CMPLX(0.0,0.0)
      T(2,1)=CMPLX(0.0,0.0)
```

```
C**********************************************************
C
C    Calculate attenuation Ratio                    (eqn 36)
C
C**********************************************************

C    Establish Constants
C     arbitrary values are used. Specific values can be
C     substituted or read in as previously used parameters
C     were.
      SIGMA=1.0
      R2=1.0
      IDYAD(1,1)=CMPLX(1.0,0.0)
      IDYAD(1,2)=CMPLX(0.0,0.0)
      IDYAD(2,1)=CMPLX(0.0,0.0)
      IDYAD(2,2)=CMPLX(1.0,0.0)
      SIGMA2=SIGMA/(4.0*PI*R2**2)**2

C    Multiply matrix by a constant

      DO 270, K=1,2
      DO 275, J=1,2
      ATNRAT(K,J)=R(K,J)*CMPLX(SIGMA2,0.0)
  275 CONTINUE
  270 CONTINUE

      DO 300, K=1,2
      DO 310, J=1,2
      ATNRAT(K,J)=IDYAD(K,J)-ATNRAT(K,J)
  310 CONTINUE
  300 CONTINUE

C    Invert matrix

      DET=ATNRAT(1,1)*ATNRAT(2,2)-ATNRAT(1,2)*ATNRAT(2,1)
      C(1,1)=ATNRAT(2,2)/DET
      C(1,2)=CMPLX(-1.0,0)*ATNRAT(1,2)/DET
      C(2,1)=CMPLX(-1.0,0)*ATNRAT(2,1)/DET
      C(2,2)=ATNRAT(1,1)/DET

C    Multiply matrix
```

```
      DO 320 K=1,2
      DO 330 J=1,2
      ATNRAT(K,J)=C(K,1)*T(1,J)+C(K,2)*T(2,J)
  330 CONTINUE
  320 CONTINUE


C    Multiply matrix

      DO 340 K=1,2
      DO 350 J=1,2
      C(K,J)=T(K,1)*ATNRAT(1,J)+T(K,2)*ATNRAT(2,J)
  350 CONTINUE
  340 CONTINUE

C    Multiply matrix by a constant

      DO 360 K=1,2
      DO 370 J=1,2
      ATNRAT(K,J)=C(K,J)*CMPLX(SIGMA2,0.0)
  370 CONTINUE
  360 CONTINUE

C    Add matrix and multiply by a constant

      DO 380, K=1,2
      DO 390, J=1,2
      ATNRAT(K,J)=(R(K,J)+ATNRAT(K,J))/CMPLX(SIGMA,0.0)
  390 CONTINUE
  380 CONTINUE

C************************************************************
C
C    Write Attenuation Ratio to Screen and File
C
C************************************************************

      PERPDB=LOG10(CABS(ATNRAT(1,1)))*10.0
      PARDB=LOG10(CABS(ATNRAT(2,2)))*10.0

      WRITE (*,550)THETAI,PERPDB,PARDB
      WRITE (1,550)THETAI,PERPDB,PARDB
```

```
  550 FORMAT(F12.3,F12.3,F12.3)

  700 CONTINUE

      CLOSE(UNIT=1)

      STOP
      END
```

Program SIGMA *Listing*

```
C                          PROGRAM SIGMA


C************************************************************
C
C     This program is designed to predict the attenuation
C     of the radar cross section of a circular flat plate
C     target at angles of incidence from 0 to 90 degrees due
C     to the deployment of a camouflage netting system.
C     It does this by calculating complex transmission
C     and reflection dyads, given complex constitutive
C     parameters.
C     Output data are echoed to the screen and saved
C     in the file SIGMA.DAT
C
C     Parenthetical numbers in comment statements refer
C     to equation numbers in the body of the thesis.
C
C************************************************************
C
C     Constants used:
C
C      EP0      = permittivitty of free space
C      MU0      = permeability  of free space
C      I        = square root of -1
C      PI       = 3.14...
C      IDYAD    = Identity dyad
C      F        = frequency of incident radiation (GHz)
C      W        = angular frequency of incident radiation
C      D        = thickness of net
```

```
C     THETAI  = incidence angle radiation on the target
C     R2      = distance separating net and target
C     SIGMA   = radar cross section of target
C    Calculated variables
C     THETAN  = path angle of radiation in net
C     THENET  = incidence angle radiation on the net
C     EPN     = permittivitty of net material
C     MUN     = permeability  of net material
C     KN      = wave number of net
C     KO      = wave number of free space
C     Z       = complex impedance
C     R       = Reflection coefficient
C     T       = Transmission coefficient
C     ALPHA   = Attenuation angle
C     ATNRAT  = Dyadic attenuation ratio
C
C     The following are simply used as intermediate
C      variables in the calculation of one or more
C      of the above:
C
C     EPR, EPI, MUR, MUI, AASIN, TANA, SIGMA2, C, DET
C
C************************************************************

C    Housekeeping details

      REAL THETAI,THETAR,LAMBDA
      REAL EPR,EPI,EPO
      REAL MUR,MUI,MUO,KO
      COMPLEX EPN,MUN,KN,AASIN,THETAN,ALPHA
      DIMENSION Z(2,2),R(2,2),T(2,2),C(2,2)
      DIMENSION IDYAD(2,2),ATNRAT(2,2)
      COMPLEX Z,TANA,R,T,I,ATNRAT,IDYAD,C,DET
      OPEN(1,STATUS='NEW',FILE='SIGMA.DAT')

C    Establish constants

      PI=3.141592624
      EPO=1E-9/(36*PI)
      MUO=400*PI*1E-9
      I=CMPLX(0.0,1.0)
```

```
C***********************************************************
C
C    Read in measurable variables and adjust units.
C
C***********************************************************

      F=10.0
      D=0.5
      EPR=1.0
      EPI=0.01
      MUR=1.0
      MUI=0.0

C    Calculate angular frequency
      F=F*1E9
      LAMBDA=3.0E8/F
      W=2*PI*F

C    Adjust units and form complex parameters

      D=D/100.0
      EPN=CMPLX(EPR,EPI)*CMPLX(EP0,0.0)
      MUN=CMPLX(MUR,MUI)*CMPLX(MU0,0.0)

C***********************************************************
C
C    Recap input data to screen and file
C
C***********************************************************

      WRITE (*,128)
      WRITE (1,128)
  128 FORMAT(1X,'Recap of input data:',I2)
      WRITE (*,129) F,D,EPN,MUN
      WRITE (1,129) F,D,EPN,MUN
  129 FORMAT(1X,'frequency   =',E10.3,' Hz'/,1X,'thickness   =',F10.5,'
     .meters'/,1X,'epsilon     =',E10.3,'+ j',E10.3,' Farads/meter'/,1X,
     .'mu          =',E10.3,'+ j',E10.3,' Henrys/meter',//)

      WRITE (*,200)
      WRITE (1,200)
  200 FORMAT(//,23X,'Attenuation Ratio (dB)')
```

```
      WRITE (*,215)
      WRITE (1,215)
  215 FORMAT(5X,'angle of',5X,'RCS',12X,'polarization:')
      WRITE (*,220)
      WRITE (1,220)
  220 FORMAT(4x,'incidence',14x,'perpendicular   parallel')

C     Begin loop for aspect angles

      DO 700, M=1,90

C************************************************************
C
C     Calculate intermediate variables
C
C************************************************************

      THETAI=REAL(M)
      THETAR=THETAI*PI/180.0
      THENET=ASIN(7.5/12.5*SIN(THETAR))

C     Calculate Complex wave numbers
      KO=W*SQRT(EPO*MUO)
      KN=W*CSQRT(EPN*MUN)
      AASIN=CSIN(CMPLX(THENET,0.0))*(KN/KO)
C    Determine thetaN (complex arcsin of AASIN)                  (eqn 22)
      THETAN=CMPLX(0.0,-1.0)*CLOG(I*AASIN+CSQRT(CMPLX(1.0,0.0)-AASIN**2)
     .)

C************************************************************
C
C     Calculate Complex impedances             (eqn 18,19,20)
C
C
C     Complex impedances, and transmission and reflection
C       coefficients are in the form  are in the form:
C       Z(p,m), R(p,m), and T(p,m), respectively.
C       where the first dimension, p, denotes the polarization:
C                (1=perpendicular or 2=parallel)
C       and the second, m, denotes the medium:
C                    (1=air and 2=the net)
C
```

```
C*************************************************************

      Z(1,1)=CMPLX((1/COS(THENET))*(SQRT(MU0/EP0)),0.0)
      Z(1,2)=(CMPLX(1.0,0.0)/CCOS(THETAN))*(CSQRT(MUN/EPN))
      Z(2,1)=CMPLX((COS(THENET))*(SQRT(MU0/EP0)),0.0)
      Z(2,2)=(CCOS(THETAN))*(CSQRT(MUN/EPN))
      ALPHA=((CMPLX(K0,0.0))/KN)**2*CMPLX((SIN(THENET)**2),0.0)
      ALPHA=KN*CMPLX(D,0.0)*(CSQRT(CMPLX(1.0,0.0)-ALPHA))

C*************************************************************
C
C    Calculate Fresnel coefficients
C
C*************************************************************

C    Calculate the complex tangent of alpha
      TANA=CSIN(ALPHA)/CCOS(ALPHA)
      DO 250 L=1,2
C    Calculate reflection coefficient                        (eqn 23)
      R(L,L)=(I*(Z(L,1)**2-Z(L,2)**2)*TANA)/((CMPLX(2.0,0.0)*Z(L,1)*Z(L,
     .2))-I*(Z(L,1)**2+Z(L,2)**2)*TANA)
C    Calculate transmission coefficient                      (eqn 24)
      T(L,L)=(CMPLX(2.0,0.0)*Z(L,1)*Z(L,2))/(CMPLX(2.0,0.0)*Z(L,1)*Z(L,2
     .)*CCOS(ALPHA)-I*(Z(L,1)**2+Z(L,2)**2)*CSIN(ALPHA))
  250 CONTINUE
      R(1,2)=CMPLX(0.0,0.0)
      R(2,1)=CMPLX(0.0,0.0)
      T(1,2)=CMPLX(0.0,0.0)
      T(2,1)=CMPLX(0.0,0.0)

C*************************************************************
C
C    Calculate attenuation Ratio                  (eqn 36)
C
C*************************************************************

C    Establish Constants
C     arbitrary values are used. Specific values can be
C     substituted or read in as previously used parameters
C     were.
      R2=1.0
      IDYAD(1,1)=CMPLX(1.0,0.0)
```

```
      IDYAD(1,2)=CMPLX(0.0,0.0)
      IDYAD(2,1)=CMPLX(0.0,0.0)
      IDYAD(2,2)=CMPLX(1.0,0.0)

C    Determine RCS of target
C      The target is a cicular, perfectly conducting flat
C      plate of radius A and an area of one square meter.
C      (Ruck equation 7.5-13)
c      Formula is based on thetai=0 at normal incidence

c      THETAI=90.0-THETAI
c      THENET=PI/2-THENET

C      Formula is invalid for thetai= 0 and 90 degrees

      IF (THETAI .EQ. 0.0) GOTO 700
      IF (THETAI .EQ. 90.0) GOTO 700

      A=SQRT(1.0/PI)
      ARG=2.0*K0*A*SIN(THETAR)

C    Carry out multiplication with logarithms to avoid
C       floating point error.
      SIGMA=(LAMBDA**2.0*K0*A)/(4*PI**2.0*SIN(THETAR))*(COS(ARG)**2.0+10
     ..0**(LOG10(SIN(ARG)**2.0)+LOG10(SIN(THETAR)**(-2.0))))

      SIGMA2=SIGMA/(4.0*PI*R2**2)**2

C    Multiply matrix by a constant

      DO 270, K=1,2
      DO 275, J=1,2
      ATNRAT(K,J)=R(K,J)*CMPLX(SIGMA2,0.0)
  275 CONTINUE
  270 CONTINUE

      DO 300, K=1,2
      DO 310, J=1,2
      ATNRAT(K,J)=IDYAD(K,J)-ATNRAT(K,J)
  310 CONTINUE
  300 CONTINUE
```

```
C     Invert matrix

       DET=ATNRAT(1,1)*ATNRAT(2,2)-ATNRAT(1,2)*ATNRAT(2,1)
       C(1,1)=ATNRAT(2,2)/DET
       C(1,2)=CMPLX(-1.0,0)*ATNRAT(1,2)/DET
       C(2,1)=CMPLX(-1.0,0)*ATNRAT(2,1)/DET
       C(2,2)=ATNRAT(1,1)/DET

C     Multiply matrix

       DO 320 K=1,2
       DO 330 J=1,2
       ATNRAT(K,J)=C(K,1)*T(1,J)+C(K,2)*T(2,J)
   330 CONTINUE
   320 CONTINUE


C     Multiply matrix

       DO 340 K=1,2
       DO 350 J=1,2
       C(K,J)=T(K,1)*ATNRAT(1,J)+T(K,2)*ATNRAT(2,J)
   350 CONTINUE
   340 CONTINUE

C     Multiply matrix by a constant

       DO 360 K=1,2
       DO 370 J=1,2
       ATNRAT(K,J)=C(K,J)*CMPLX(SIGMA2,0.0)
   370 CONTINUE
   360 CONTINUE

C     Add matrix and multiply by a constant

       DO 380, K=1,2
       DO 390, J=1,2
       ATNRAT(K,J)=(R(K,J)+ATNRAT(K,J))/CMPLX(SIGMA,0.0)
   390 CONTINUE
   380 CONTINUE

C************************************************************
```

```
C
C    Write Attenuation Ratio to Screen and File
C
C***********************************************************

      PERPDB=LOG10(CABS(ATNRAT(1,1)*cmplx(sigma,0.0)))*10.0
      PARDB=LOG10(CABS(ATNRAT(2,2)*cmplx(sigma,0.0)))*10.0
      SIGMADB=LOG10(SIGMA)*10.0

      WRITE (*,550)THETAI,SIGMADB,PERPDB,PARDB
      WRITE (1,550)THETAI,SIGMADB,PERPDB,PARDB
  550 FORMAT(F12.3,F12.3,F12.3,F12.3)

  700 CONTINUE

      CLOSE(UNIT=1)

      STOP
      END
```

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Vita

Major John B. MacLeod was born June 20, 1954 in Lansing, Michigan. He graduated from high school in Gambrills, Maryland in 1972 and entered the United States Military Academy, West Point, New York, from which he graduated with a Bachelor of Science degree in 1976. Upon graduation, he received a commission in the US Army Corps of Engineers and served in a variety of combat engineering and construction engineering assignments until entering the School of Engineering, Air Force Institute of Technology, in June 1987. He holds a Master of Science degree in Engineering Management from the University of Missouri, Rolla, Missouri, and is registered as a Professional Engineer in the state of Virginia.

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) AFIT/GE/ENG/89J-2	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION School of Engineering	6b. OFFICE SYMBOL (If applicable) AFIT/ENG
7a. NAME OF MONITORING ORGANIZATION	
6c. ADDRESS (City, State, and ZIP Code) Air Force Institute of Technology Wright-Patterson AFB, OH 45433-6583	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Belvoir RD&E Center	8b. OFFICE SYMBOL (If applicable) STRBE-JD
9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER	
8c. ADDRESS (City, State, and ZIP Code) Camouflage Research Team Countersurveillance and Deception Div Fort Belvoir, VA 22060-5606	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)

MODELING OF CAMOUFLAGE NETTING FOR RADAR CROSS SECTION ANALYSIS

12. PERSONAL AUTHOR(S)
John B. MacLeod, MAJ, USA

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
MS Thesis	FROM ____ TO ____	1989 June	78

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
17	04	03
17	09	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

Radar Camouflage, Radar Cross Section
Radiation Attenuation

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Thesis Chairman: Dr. Vital Pyati

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL Vital Pyati	22b. TELEPHONE (Include Area Code) (513) 255-3576 / 22c. OFFICE SYMBOL AFIT/ENG

DD Form 1473, JUN 86 Previous editions are obsolete. SECURITY CLASSIFICATION OF THIS PAGE

Abstract

An analytical model for radar cross section reduction by the US Army's currently deployed camouflage netting system was developed. This model was needed to assist in the evaluation of developmental camouflage materials through prediction of radar cross section reduction. With this model, parameters measurable in the laboratory can be used to predict the performance of fabricated netting.

Using a physical optics approach to modeling, the net is modeled as a layer of lossy dielectric material. The layer is assumed to be a continuous, locally flat, and locally homogeneous medium. Relevant equations are then developed to predict radar cross section reduction. The constitutive parameters of interest are the complex permittivity and permeability and the effective thickness of the net. Methods of obtaining or approximating these values are discussed.

The development provides a prediction equation using a dyadic description of the electric fields on either side of the nets, developed from the constitutive parameters, from which a prediction of radar cross section reduction follows. Values for constitutive parameters are assumed to generate data for comparative purposes.

Using this model with the measured complex constitutive parameters of the net, an anticipated reduction of RCS can be predicted.